Pole Type Constant Potential Transformers.—(Westinghouse Co.)

Frontispiece.

DESIGN

OF

ELECTRICAL MACHINERY

A TREATISE FOR THE USE, PRIMARILY, OF STUDENTS IN ELECTRICAL ENGINEERING COURSES

VOL. II.

ALTERNATING CURRENT TRANSFORMERS

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PREFACE

THE purpose of this volume is to supply a manual on Transformer Design. It contains what the author believes will be of most service to the student who is just entering upon his experience as a designer.

Good electrical apparatus cannot be designed by any set of rules, and it must be recognized that it is not, in general, feasible to develop a real designer in a college course. However, there are certain fundamental scientific principles which can be laid down definitely and taught with precision. The student should bear in mind that while there is much in this volume that is of practical value, the main object is to present as clearly and briefly as possible the fundamental principles upon which the design necessarily rests. He also should bear in mind that he cannot expect to get any more than a training that will be of value and assistance to him, if at any time in his later experience he should decide to become a designer.

An electrical designer must also be a mechanical designer. This point is very often overlooked by the beginner. It is possible to devise some very wonderful designs from an electrical standpoint, but which when the mechanical features are considered are absolutely impractical.

The design of direct-current dynamos was covered in Volume I. Alternators, synchronous motors, rotary con-

verters, induction motors and switchboards will be covered in succeeding volumes.

Special attention has been given to the arrangement of the work with regard to the order of the process of making the calculations.

The author has drawn very largely upon information obtained from the Manufacturing Companies. He desires to acknowledge his indebtedness to the above companies; and to express his appreciation of their courtesy for permission for use of illustrative cuts, drawings, etc., also to many others whose valuable suggestions have been utilized in preparing this work.

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MINNEAPOLIS, MINN.,
Jan. 1, 1912.

CONTENTS

CHAPTER I

PAGE

Development of Alternating Current Transformers............ 1

CHAPTER II

Varieties of Transformers and Their Characteristics.......... 12

CHAPTER III

Method of Designing Constant-Potential Alternating-Current Transformers... 31

CHAPTER IV

Illustrative Designs... 57

DESIGN OF ELECTRICAL MACHINERY

VOLUME II

ALTERNATING CURRENT TRANSFORMERS

DESIGN OF ELECTRICAL MACHINERY

VOLUME II.—ALTERNATING-CURRENT TRANSFORMERS

CHAPTER I

DEVELOPMENT OF ALTERNATING-CURRENT TRANSFORMERS

THE alternating-current transformer consists of one or more magnetic circuits interlinked with two electric circuits, one of which (the primary) receives electrical

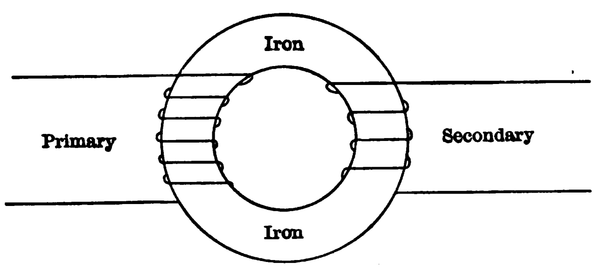


FIG. 1.—Faraday Ring.

energy at a prescribed voltage, and the other (the secondary) delivers this same energy minus the necessary losses in the transformer (usually) at a different voltage.

In following out the development of the transformer, we find that improvements have been made by a process of evolution in which rudimentary forms were successively

replaced by more and more completely developed designs. The prototype of the modern transformer is Faraday's iron ring (Fig. 1), with which he made the initial discovery of electro-magnetic induction.

Faraday's initial transformer consisted of an iron ring about seven-eighths of an inch thick and six inches in external diameter. On one side were wound a number of turns of wire separated by twine and calico. On the other side of the ring but separated from the first winding by an

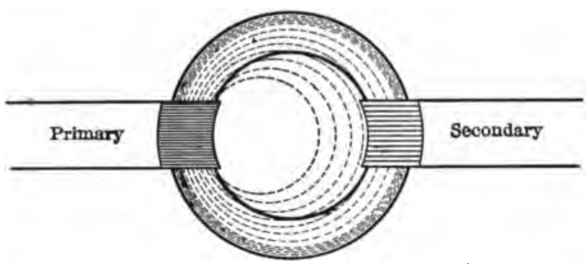


Fig. 2.—Diagram Illustrating Magnetic Leakage.

interval was placed a second winding. He found that when the connection of a battery to the first winding was broken an electromotive force was induced in the second winding.

Since the lines of force not only pass through the iron, but to some extent through the air (Fig. 2), it follows that only a part of the magnetic flux in the primary coil actually threads through the secondary coil, the rest closing around the primary coil in air. The difference in flux in the primary and secondary coils will be greater the farther the coils are from each other, and the greater the reluctance of the iron circuit. The result is that a portion of the lines of force are caused to leak out laterally and produce a leakage

field which does not in any way contribute to the production of electromotive force in the secondary coil. The arrangement of coils in Fig. 1 is bad on account of their great distance. It does not give a strong magnetic flux through the core if a large current be taken from the secondary.

The conditions which influence leakage can best be understood by assuming that the primary coil carries a continuous current, while through the secondary there passes either no current, or else a continuous current in such a direction as will tend to weaken the field produced by the primary current. The primary current must then be sufficiently large to tend to produce a field equal to, but opposed in direction to the field which the current in the secondary tends to produce, and in addition it must produce the actual flux present in the transformer. The primary coil, therefore, drives a magnetic flux in a certain direction through the core. If no current flows in the secondary then the lines of force have only the reluctance of the iron path to overcome which will be so small that only a few of the lines of force will be crowded out. If, however, the secondary also carries a current it will tend to produce a flux in the opposite direction, which colliding with the original flux causes considerable leakage, thus weakening considerably the flux actually passing through the secondary coil. This reasoning applies to the case of alternating currents provided that the change in direction occurs in both coils nearly simultaneously, a condition which is always fulfilled in transformers working under load.

With the arrangement shown in Fig. 1 the leakage is very large. The design may be improved by spreading

each of the coils over one-half of the circumference as shown in Fig. 3. As regards leakage, this is an improvement

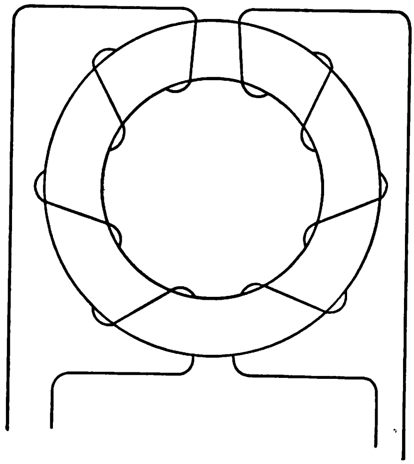


FIG. 3.—Spreading of Coils to Reduce Magnetic Leakage.

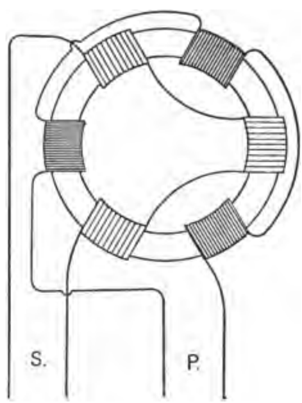


FIG. 4.—Sub-division of Coils to Reduce Magnetic Leakage.

over Fig. 1. The improvement may be carried still further by subdividing each coil into several parts. Fig. 4 shows six separate coils arranged to cover the ring uniformly,

and connected alternately with the primary and secondary circuit. The leakage field is now only about one-ninth of

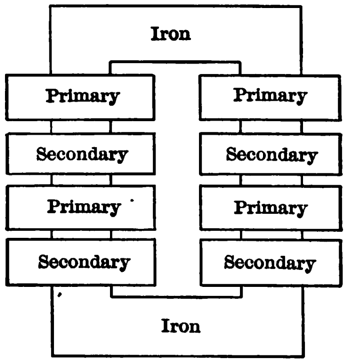


Fig. 5.—Sub-divided Coils on Rectangular Core (Core Type).

its previous value. If, instead of subdividing each coil into three parts, it were subdivided into four, the leakage would be only one-sixteenth of its previous value, etc. By carrying the principle of subdivision far enough, the

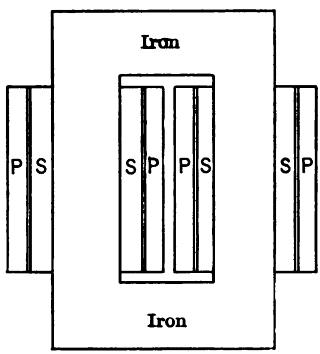


Fig. 6.—Co-axial Coils on Rectangular Core (Core Type).

leakage field may be reduced to such an extent that its effect is practically negligible.

For geometric and practical reasons, the shape of the magnetic link was changed from a circle to a rectangular frame, and the coils placed on the two longer sides of the rectangle (Fig. 5).

In the arrangement shown in this diagram, the primary winding is subdivided into four coils which alternate in position with the four coils of the secondary winding. A more usual and equally effective arrangement as regards

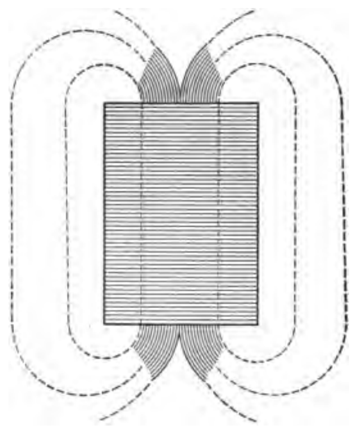


FIG. 7.—Hedgehog Transformer.

leakage consists in placing the coils axially within each other (Fig. 6).

This reduces the number of coils to be wound and handled and simplifies the insulation between the primary and secondary coils.

One of the early investigators, J. Swinburne, introduced the so-called "hedgehog" transformer (Fig. 7) with the intention of reducing the iron loss. He placed the coils upon a core consisting of a bundle of iron wires with their ends spread out like the back of a hedgehog. The lines

of force passing through the core must complete their path through air, as shown in the diagram. Hysteresis loss takes place only in the small quantity of iron which forms the core proper. The actual iron loss is very little, if any, less than it is in the closed magnetic circuit types. This type of transformer requires an exceedingly large exciting current. With the secondary open the primary current may be as much as 50 per cent of full-load current, whereas

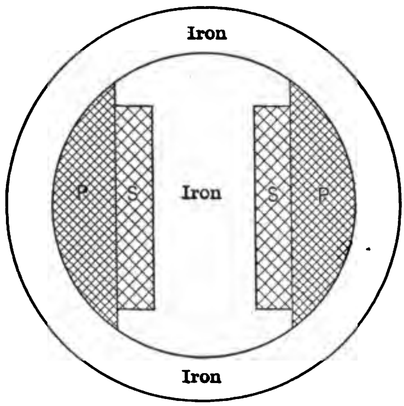


Fig. 8.—Shuttle Transformer.

in the closed magnetic circuit types, it is only a very small fraction of full-load current. This type of transformer did not prove itself successful in practice.

One of Rankin Kennedy's early specifications describes a transformer made with a shuttle-shaped core, constructed out of a pile of iron stampings, insulated from one another and pressed together, over which were wound the primary and secondary windings. The magnetic circuit was completed by winding iron wires over the shuttle-shaped coil, the direction of such windings being perpendicular to the axis of the core.

Transformers now in use may be divided into two great groups:

I. Those with distributed coils.

II. Those with distributed magnetic circuits.

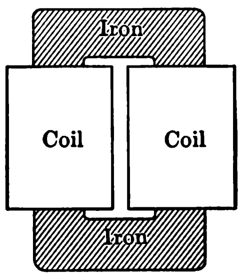


FIG. 9.—Distributed Coil Type (Core).

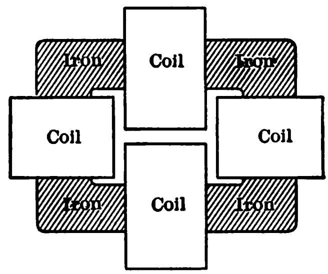


FIG. 10.—Distributed Coil Type (European).

The types shown in Figs. 9 and 10 belong to the first group, and those shown in Figs. 11, 12, 13, 14 and 15 belong to the second group.

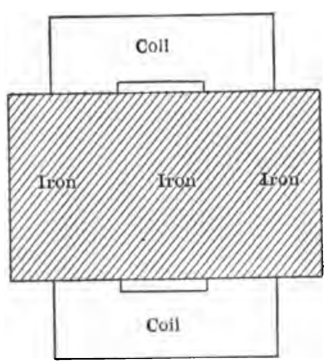


FIG. 11.—Distributed Magnetic Circuit (Small Shell Types).

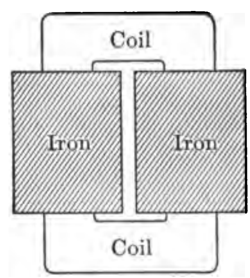


FIG. 12.—Distributed Magnetic Circuit (Large Shell Types).

Which of the two general types is the better cannot generally be decided upon, but depends upon a variety of circumstances.

With distributed coils the weight of iron is small, and the length of the turns of wire is short. The path of the flux, however, is very long, hence the number of turns is

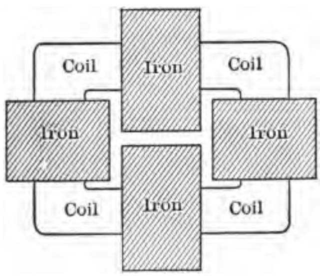


Fig. 13.—Distributed Magnetic Circuit Type.

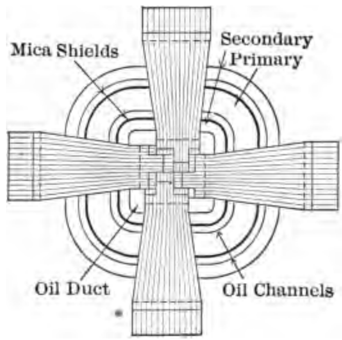


Fig. 14.—Distributed Magnetic Circuit (G. E. Co.).

large, since the number of ampere turns required to produce the flux is large. The total weight of copper is therefore rather large, but the coils are accessible, and more exposed to the cooling effects of the oil.

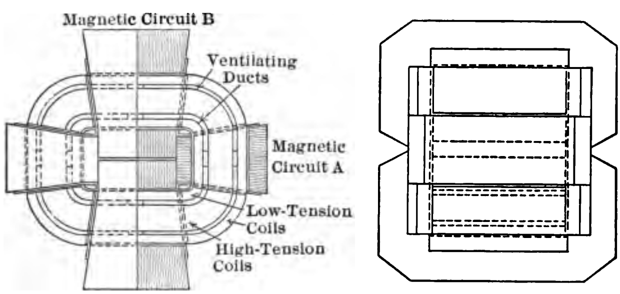


Fig. 15.—Distributed Magnetic Circuit (Westinghouse Co.).

With a distributed magnetic circuit, the length of the magnetic circuit is short, hence fewer ampere turns are required to produce the flux. The coils have fewer turns,

but much longer turns. The total weight of copper is, however, rather small. It permits of a simpler and better mechanical construction, since the coils are protected from mechanical injury. It requires more iron thus increasing the iron loss and making it difficult to get a high all-day efficiency. The coils are not readily accessible or so well exposed to the cooling effect of the oil. The leakage flux

FIG. 15a.—Distributed Magnetic Circuit (Westinghouse).

is a little larger than with the other type, thus tending to make the regulation a little poorer. If the transformer is damaged by lightning, repairs are more easily made. If a damaged distributed-magnetic-circuit transformer is repaired " on the ground " it will usually be found impossible to replace all the iron. This simply means more iron loss, higher temperature rise and hence a little lower efficiency. With the distributed-coil type, especially the smaller sizes, it will often be found impossible to replace all of the wire. This means that not only the temperature rise is increased,

and the efficiency lowered, but the ratio of transformation is changed, hence the voltage available at the secondary terminals is no longer the same.

The later types give a better opportunity for getting away from the old so-called "mummifying" methods of insulating which formerly prevailed in transformers, and the making use of the "skeletonized" constructions and heat dissipating and impregnating compounds. The coils can be made up so as to constitute rigid cylinders which may be slipped off the winding form and upon the iron core of the transformer. The core may be separated from the windings and the windings from each other by fibrous strips, thus leaving channels for the air or oil to circulate through. A cylinder of micanite or other material may be slipped in between the primary and secondary windings, and this in turn may be separated from the windings by insulating strips providing still more channels for the air and oil to circulate through. Wrapping should be avoided and distance strips freely employed as far as practicable, in the interests of obtaining good surface radiation and avoiding great depths of unventilated windings.

A good transformer of any type must have the core losses, copper losses, regulation and quality of insulation correctly proportioned in order to secure the best average results.

CHAPTER II

VARIETIES OF TRANSFORMERS AND THEIR CHARACTERISTICS

THE varieties of transformers met with in commercial practice are as follows:

(*a*) Constant potential transformers.
(*b*) Constant current transformers.
(*c*) Series transformers.
(*d*) Auto-transformers.
(*e*) Rotary transformers. (As this type is inherently a synchronous A.-C. motor, it will not be discussed in this volume).

Constant-potential Transformers

Regulation. The function of this type is to receive electrical energy at a prescribed e.m.f. and to deliver it with as little variation as possible in the secondary e.m.f. at all loads and at different power factors.

The American Institute of Electrical Engineers defines regulation as follows: "In constant-potential transformers, the regulation is the ratio of the rise of secondary terminal voltage from rated non-inductive load to no load (at constant primary impressed voltage) to the secondary terminal voltage at rated load." It is further required that the frequency be kept constant, and that the wave of impressed e.m.f. be sinusoidal. The transformer must also operate without excessive rise in temperature, such excessive rise being injurious to the insulation and reducing the efficiency. The temperature rise, as measured by increase

in resistance of the coils, should not exceed 50° C. above the surrounding air.

In a modern transformer the magnetic leakage is so small that for unity power factor its effect on the regulation is practically nil. The primary impressed e.m.f. minus the

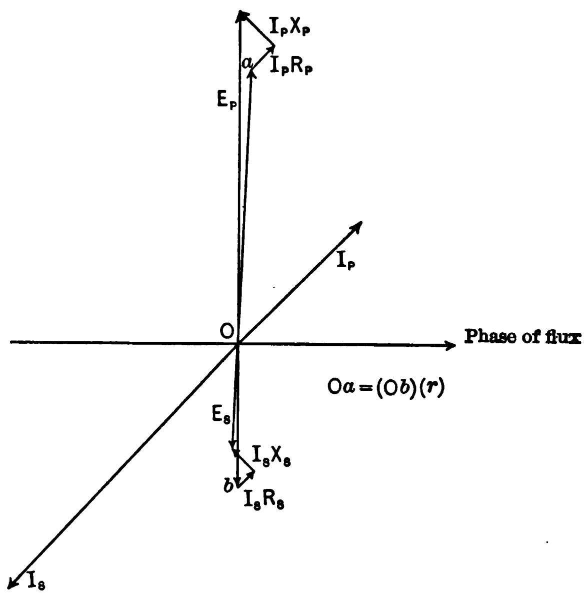


FIG. 16.

I_pR_p volts expended in overcoming the resistance of the primary coil is operative in producing secondary pressure. I_sR_s volts are further expended in overcoming the resistance of the secondary coil. A part of the impressed e.m.f. is used in overcoming the inductive drop I_pX_p and I_sX_s due to the leakage flux. The inductive decrements I_pX_p and I_sX_s are approximately at right angles to the primary impressed e.m.f., E_p, and the secondary e.m.f., E_s, so long as the power factor is unity, therefore, do not reduce them appre-

ciably. A lagging power factor will cause I_pX_p and I_sX_s to reduce the regulation more and more as the angle which I_p makes with the base line decreases.

From Fig. 16 it is evident that certain leading power factors might cause the regulation to be even better than it is when the power factor is unity. It is possible in some cases to insert such an amount of capacity into the secondary circuit that a regulation of 100 per cent is obtained. The following table shows the regulation of a line of transformers built by one of the most reputable manufacturers. These values were given out in 1907. Although very good, some improvement has been made since then. The core losses have been reduced considerably.

TABLE I

DATA BASED ON 1100 OR 2200 VOLTS 60 CYCLES, SINE WAVE SECONDARY VOLTS 110 OR 220

Kilowatt	Core Loss.	Copper Loss.	Per cent Reg.	Full Load.	Efficiency. ¾ Load.	Efficiency. ½ Load.	Efficiency. ¼ Load.	Net Weight in Lb. Inc. Oil.
.6	21	15	2.54	94.3	93.9	92.4	87.2	90
1	27	24	2.45	95.2	94.9	93.8	89.8	100
1.5	32	34	2.30	95.8	95.7	94.9	91.7	160
2	37	45	2.28	96.1	96.0	95.4	92.6	165
2.5	41	53	2.15	96.4	96.4	95.8	93.4	195
3	45	61	2.08	96.6	96.6	96.1	93.9	200
4	55	74	1.92	96.9	96.9	96.5	96.4	295
5	62	90	1.90	97.1	97.1	96.7	94.9	325
7.5	84	122	1.75	97.3	97.4	97	95.3	400
10	102	149	1.59	97.6	97.6	97.3	95.9	450
15	137	209	1.51	97.7	97.8	97.5	96.2	810
20	162	268	1.42	97.9	98	97.8	96.6	900
25	187	311	1.31	98.1	98.1	97.9	96.8	1175
30	210	359	1.25	98.1	98.2	98	97	1230
40	258	450	1.20	98.3	98.3	98.2	97.2	1580
50	307	540	1.15	98.3	98.4	98.3	97.3	1615

Fig. 17 indicates what may be expected in the way of regulation at 80 per cent power factor as compared to the regulation at 100 per cent power factor. The regulation on power factors in between is about in proportion.

Losses. The second column of Table I shows the core losses which are the same at all loads since the frequency and flux density remain constant. Column 3 shows the copper losses which vary as the square of the primary and

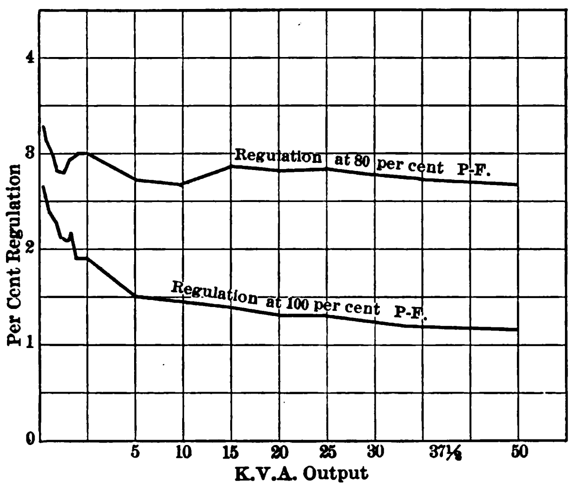


FIG. 17.—Curves showing Regulation of Transformers of Recent Design (N.E.L.A. Proceedings, Vol. I, 1909).

secondary currents. Fig. 18 contains curves showing the copper loss, the core loss and the total loss at various loads for a 5-KW. transformer.

Efficiency. Fig. 18 also shows the efficiency for the same transformer. The efficiency reaches its maximum value in this case at three-fourths load, is the same at full load, and falls off slightly on one and one-fourth load. The location of the highest efficiency point depends, of

course, upon the relation of the copper and iron losses. A transformer may therefore be designed to suit a large or small average load. There is, however, another very important consideration which should not be overlooked, i.e., the total cost of supplying to the transformer its losses.

In supplying transformer losses the actual cost of generating current, say one-half cent per kilowatt hour,

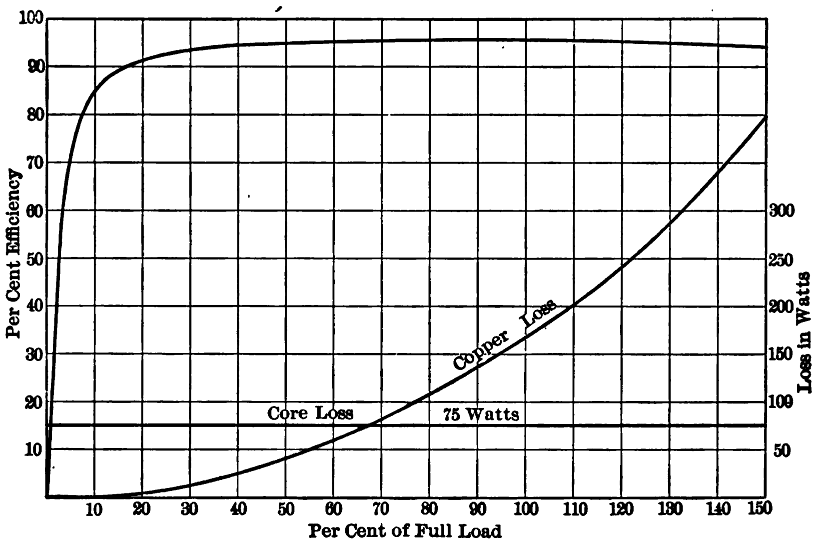


FIG. 18.—Curves showing Variation of Losses and Efficiency with Load, for a 5-KW. Transformer.

and a fixed charge for interest, taxes, depreciation, etc., on the station equipment of say, 13 per cent on $150 or $19.50 per kilowatt capacity is what should be considered in calculating the cost of these losses. Assuming a daily load on the transformer to be equivalent to five hours of full load, the actual cost of the power used for supplying the copper loss of the 10-KW. transformer of Table I, will be:

Fixed charge equals	.149×$19.50=$2.91	
Cost of 149 watts for 5 hours per day for 365 days at $.005 per kilowatt hour equals		1.36
Total cost		$4.27

The core losses are supplied for 24 hours a day for 365 days. The cost of the core losses would be:

Fixed charge	.102×$19.50=$1.99	
Cost of 102 watts for 24 hours per day for 365 days at $.005 per kilowatt hour		= 4.47
Total cost		$6.46

It is to be noted that the total cost of the iron losses are considerably larger than the total cost of the copper losses, and that the total amounts to over $1 per kilowatt transformer capacity. The total losses in the above transformer is 149 plus 102 = 251 watts. If the core losses were only one-third of the total loss and the copper losses the other two-thirds, the cost of supplying the losses would be less under the above conditions. Suppose the core loss were 84 watts, and the copper loss 167 watts, a total of 251 as before, the result would be as follows:

Copper loss fixed charge	.167×$19.50=$3.26	
Cost of 167 watts for 5 hours per day for 365 days at $.005 per kilowatt hour		1.52
Total cost		$4.78
Core loss fixed charge	.84×$19.50= 1.64	
Cost of 84 watts for 24 hours per day for 365 days at $.005 per kilowatt hour		3.68
Total cost		$5.32

The sum total cost of the losses in the first case is $4.27 plus $6.46 = $10.73. In the second case it is $4.78 plus

\$5.32 = \$10.10 which is \$0.63 less and represents a saving on the total of 6 per cent. It is evident that the total cost of supplying the losses would be a minimum when the total cost of the core losses and of the copper losses are equal. In the above case the total cost would be a minimum if the copper losses were approximately 2.5 times the core losses. For a transformer of given cost, however, as the iron loss is reduced, and the copper loss is increased, a point is soon reached beyond which a further decrease in the iron loss can be made only at a very large corresponding increase in the copper loss. There is another side to this problem of low iron losses and high copper losses for a given sum total of the two. In many cases the copper loss is of the greater importance. On a non-inductive load the copper loss in per cent is practically equal to the regulation in per cent. Since the copper loss determines the regulation, if regulation is of primary importance, it is desirable to have a low copper loss rather than a low iron loss. The copper losses reduce the watt-hour meter reading, whereas the iron loss is measured on the station side of the transformer. Every watt hour lost by reduction of the meter reading must be charged at the selling price of the energy, whereas a watt-hour core loss should be charged for at the rate it costs to generate it, which is usually several times less than the actual selling price. If the problem were solved on this basis, it at once becomes evident that it is just as important to keep down the copper losses as it is to have very low iron losses. It would seem therefore, that there is often a fallacy in the usual argument for extremely low iron losses, and that the anxiety on the part of some managers to get transformers in which the iron loss has been forced down to the last watt, even though

it is accomplished at the expense of the copper losses and the regulation, is a mistake; and one that almost has become a hobby.

A very elaborate theoretical investigation might be made as to what relationship should exist between the copper losses and the core losses, in order that their sum might be a minimum from the standpoint of design only. Such an investigation seems to indicate that they ought to be about equal. Now, then, if the transformer is used 24 hours a day on almost full load, it is at once evident that the copper and iron losses should be somewhere near equal in order that the cost of supplying them be a minimum. The author saw a test made on a 200 K.V.A. shell type transformer, 6600 volts, 60 cycles, in which the core losses were 1800 watts, and the copper loss 1780 watts. Another test on 100 K.V.A. 55,000 volt, 60 cycle, core type transformer, showed 1400 watts core loss and 1250 watts iron loss. Core losses have been reduced considerably since the above tests were made, therefore the author believes that in large extra high voltage transformers, the core loss should be approximately 20 per cent less than the copper loss, whereas, in small lighting transformers, it should be somewhere in the vicinity of two-thirds the value of the copper loss, if the transformer is to be used on ordinary lighting and power circuits, in order to minimize the cost per year of the transformer losses.

Another question which might arise is, why not make transformers with lower total losses than is customary in order to minimize the cost per year of supplying these losses. If the losses were reduced the transformers would cost more. If the fixed charges, say 13 per cent, on the additional cost are less than the cost of supplying the additional

losses, then it would pay to buy more efficient transformers. The losses in modern transformers are such as to give the minimum total cost under about average conditions of use.

Constant-current Transformers

Series street-lighting systems require for satisfactory operation a constant current. Since there is produced in every large power station constant potential for practically all other purposes by means of constant-potential alternating-current generators, it becomes desirable to produce constant current in the secondary with constant potential on the primary. This is usually accomplished by means of the constant current or " tub " transformer.

The primary of this transformer receives constant e.m.f. from the generator circuit and maintains, automatically, a constant current in the secondary, by the movement of the secondary coil, which is carried in guides and supported from the end of a counterweight arm provided with an adjustable counterweight. The primary and secondary coils repel each other when they are carrying current, therefore tend to take positions as far apart as possible. The maximum magnetic leakage, and hence the lowest ratio of transformation of e.m.f. occurs in this extreme position. The minimum magnetic leakage occurs when the coils are in contact, hence the highest ratio of transformation. The secondary coil is counterweighted to such an extent that it floats under load, adjusting itself automatically to a constant current over a wide variation in load. An elongated shell type magnetic current is used, and the coils are flat and well protected from mechanical energy.

The transformer is usually mounted in an oil-filled case, though some of the small ones are not enclosed. The rating is usually on the number of arc lamps for which the trans-

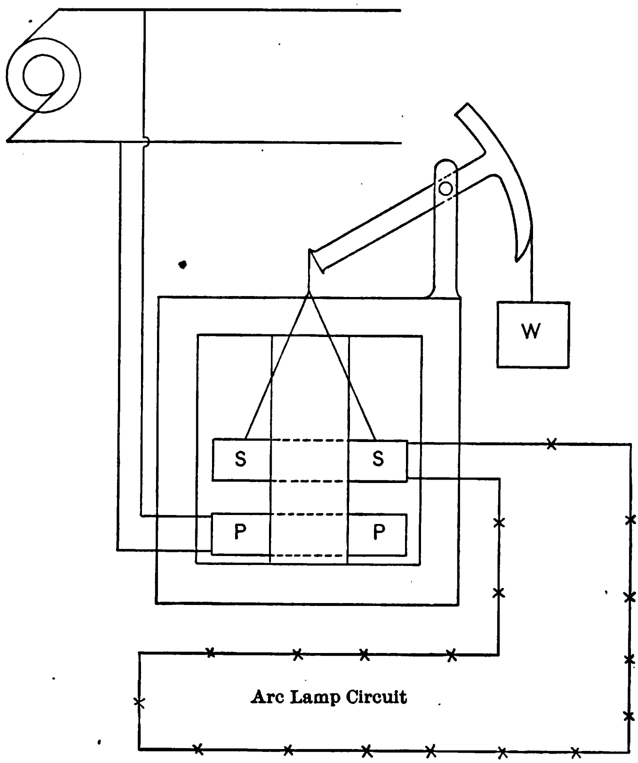


FIG. 19.—Constant-current Transformer.

former is suitable. The current is usually 6.6 amperes, and the number of lamps either 25, 50 or 100.

A constant current may also be maintained either by varying automatically the number of turns on the secondary, or by varying the impedence in the primary or secondary. The former, though it seems to have many points in its

favor, has been used commercially only on a very small scale in this country. A differential solenoid automatically changes the number of secondary turns as the strength of current through the automatically operating relay changes. In the latter scheme shown in figure 20, the circuit to the lamps is run directly from a constant potential transformer or generator, through a choke coil with variable self-induction.

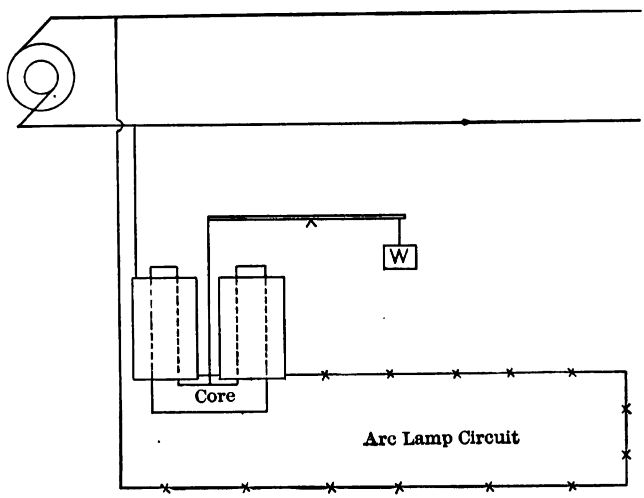


FIG. 20.—Series Arc Lamp Regulator.

The motion of the coil with respect to the core causes more or less e.m.f. to be consumed by the coil as the number of lamps in the circuit is varied.

The coil may be over the core or vice-versa, the moving part being counterweighted. This movement causes the coil to be surrounded by more or less magnetic flux, and correspondingly varies the reactance of the coil. The reactance controls the current in the circuit. The device is generally known as a CONSTANT-CURRENT REGULATOR.

It is simpler than the transformer, but the latter has the advantage of its ability to transform the e.m.f. at the same time that it is regulating the current.

Series Transformers

It is very desirable to be able to use ammeters, wattmeters, and watt-hour meters of standard sizes, and a limited range on a variety of circuits. This is accomplished by the use of series transformers. Also, very often we wish to measure the current or the power in the high-potential side of alternating-current lines, but on account

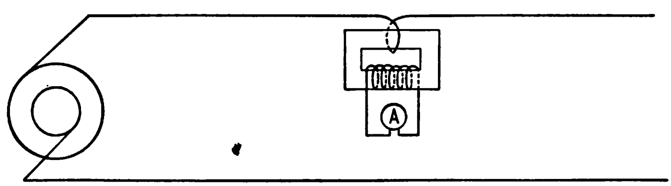


Fig. 21.—Series Transformer.

of safety do not wish to connect the instrument directly in series with the line. In such cases the metallic connection to the line is avoided by use of the series transformer.

If the primary coil of a constant-potential transformer is connected in series with a circuit, and the secondary is connected through a resistance, the secondary and primary currents will be proportional. If an ammeter is short-circuited upon the secondary of the transformer, it will indicate a current which is equal to the primary current multiplied by the inverse ratio of the turns. The connections are shown in Fig. 21.

If 1000 amperes were the maximum current in the line, a 5-ampere meter could be used if a series transformer

whose ratio were 200 to 1 were available. Series transformers are now made in small sizes and in a form convenient for switchboard work.

Series transformers are designed under the same requirements as to core loss and regulation as constant-potential transformers except that they are worked at a very low magnetic density, in order that the permeability will not vary very much as the current changes. It is readily seen that the current in the secondary depends not only on the ratio of turns, but also upon, (*a*) the resistance and reactance of the transformer itself and the instruments connected in series with it and, (*b*) on the permeability of the magnetic circuit of the transformer. To be accurate therefore, an ammeter or watt-meter must be calibrated with the series transformer with which it is to be used. On account of the change of permeability for different values of current, there will not be a straight-line relation between the primary and secondary currents. By employing a low magnetic density, however, the relationship is made to approach very closely to a straight line.

Auto Transformers

The auto transformer is a special type of constant potential transformer that is useful in special cases. Its principal use is to reduce the voltage in starting induction motors. It consists simply of a single winding tapped at different points as shown in Fig. 22.

The line e.m.f. is consumed uniformly throughout the turns. If there are 2000 turns and if 2000 volts is applied to the coil, a voltmeter connected across any part of the winding will indicate as many volts as there are turns

included between the points of contact. Current may be taken from these two points and the same winding will serve both as pr'mary and secondary. As a transformer, considered from the standpoint of efficiency, operating characteristics, etc., this method of construction is very inferior in every way to that where two separate windings are used.

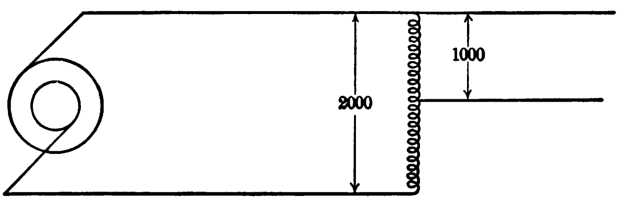


Fig. 22.—Auto-transformer.

Polyphase Transformers

In transforming polyphase e.m.f. from one voltage to polychase e.m.f. at another voltage, instead of using one transformer for each phase, one polyphase transformer may be used. A polyphase transformer consists of several single-phase transformers having portions of their magnetic circuits in common. Since these portions of the magnetic circuits carry fluxes differing in phase, an economy of material results due to the fact that the resultant flux is less than the arithmetical sum of the component fluxes. A still further saving is effected due to the necessity of only one instead of several containing tanks. Two single-phase transformers are always used on two-phase circuits. Three-phase transformers are quite generally used in Europe, and their use in this country is constantly increasing. The

magnetic circuits of the two usual types are shown diagrammatically in Fig. 23 and Fig. 24.

The advantages of three-phase type over three single-phase transformers are: (1) A saving of from 10 per cent to 20 per cent in first cost; (2) a higher efficiency, and (3) a smaller floor space is required. The cost of repairs and the cost of a spare unit are greater than if three single-phase transformers are used. Then, again, if a delta system

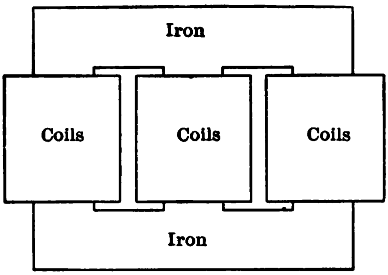


FIG. 23.—Three-phase Transformer.

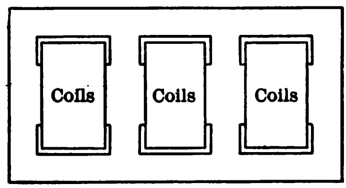


FIG. 24.—Three-phase Transformer.

of connection is used, the loss of one transformer does not mean a cessation of service.

Exciting Current in Constant-potential Transformers

When the secondary is open circuited, there is a certain amount of current flowing in the primary for the purpose of: (1) magnetizing the core, (2) supplying the core losses. This " exciting " or no-load current,flows 24 hours per day, therefore it is important to keep it as low as possible. The magnetizing component of the exciting current represents no loss of power as it is 90° out of phase with the line e.m.f. The core loss component however is a power

loss, and may be obtained by dividing the core loss in watts by the impressed e.m.f. The magnetizing component may be obtained from the following formula:

$$I_m = \frac{10\,L_m\phi}{4\pi N A \mu \sqrt{2}} = \frac{.5627\,BL_m}{N\mu};$$

where B = flux density;
L_m = length of magnetic circuit;
N = number of primary turns;
μ = permeability of the magnetic circuit at the density B.

An examination of the above formula shows that the magnetizing current is larger the greater the density and is also larger the smaller the permeability. Table II gives the permeability of ordinary transformer iron at different densities:

TABLE II

PERMEABILITY OF TRANSFORMER IRON AT DIFFERENT MAGNETIC DENSITIES

B Lines per Sq.in.	μ	*B* Lines per Sq.in.	μ
15000	2400	80000	1200
20000	2600	85000	1000
30000	3000	90000	800
35000	2950	95000	530
40000	2900	100000	360
45000	2800	105000	260
50000	2650	110000	180
55000	2500	115000	120
60000	2300	120000	80
65000	2100	125000	50
70000	1800	130000	30
75000	1500	140000	15

From the above it is evident that the magnetizing current will be much greater at high magnetic densities than at lower densities. If B is 60,000 the permeability is 2300, whereas if B is 120,000 the permeability is only 80. The magnetizing current would therefore be 58 times as large. This explains why it is that when transformers are switched on to a circuit, there are liable to be very heavy rushes of current if magnetic densities of more than about 50,000 to 60,000 lines of force per square inch are used.

In a transformer working on open circuit, assume a magnetic circuit whose area is one square inch, that the

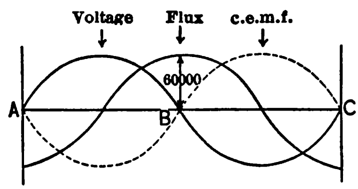


FIG. 25.

voltage wave is of sine form, that the flux wave is of similar form, lagging behind the voltage wave by 90°, as shown in Fig. 25, and that the maximum value of the flux is 60,000 lines. On open circuit the e.m.f. of self-induction is practically equal to the impressed e.m.f. The voltage wave shown is produced by the flux, and must be practically equal to the impressed e.m.f., which is shown by the dotted line. To produce the voltage wave from A to B it is necessary that the flux pass from 60,000 lines negative to 60,000 positive, which is a change of 120,000 lines. The voltage wave from A to B could also be produced by a flux curve starting from zero and reaching a maximum of 120,000 lines.

If the residual magnetism were zero and if the transformer were switched on to the circuit at the point *A* of the voltage wave, Fig. 26, i.e., at the instant of zero potential, the flux would have to start from zero and go to 120,000

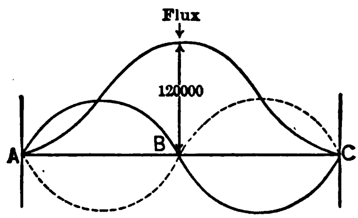


Fig. 26.

lines in order to produce a c.e.m.f. wave between *A* and *B* equal and opposite to the impressed e.m.f. From the equation for the magnetizing current it is at once evident that a very heavy magnetizing current will flow.

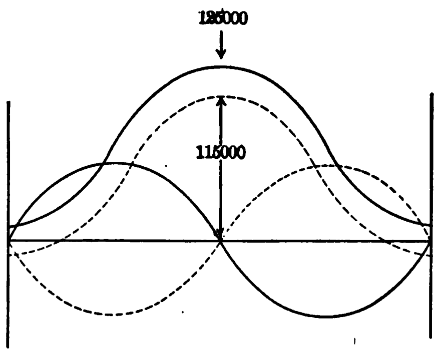


Fig. 27.

The higher the induction in the iron under normal conditions, the greater will be the saturation, hence the greater the rush of current at the instant of switching. If the switch is closed when the voltage is at its maximum point, the

flux will start at zero and go through its cycle without exceeding the normal induction and without any excess rush of current. If the switch is closed in between it will go to a point between normal induction and twice normal depending on where the voltage wave is caught. If the iron is already magnetized, when the switch is closed, and the voltage wave is caught at its zero value, the induction would go to 125,000 lines as indicated in Fig. 27, the residual being taken as 5000 lines in the positive direction. If the residual magnetism were 5000 lines negative the induction would go to 115,000 lines as indicated by the dotted line. This enormous magnetizing current soon ceases to flow because of the fact that the ohmic drop, which we have neglected so far, tends to reduce the maximum value of the flux, thus changing it from a pulsating to an alternating one, and bringing it quickly to its normal value.

Improvements in methods of design make it possible to work transformer iron at much higher densities than was customary a few years ago. Permeabilities have not been materially increased, therefore it follows that modern transformers are more subject to rushes of current at switching than the older designs.

CHAPTER III

METHOD OF DESIGNING CONSTANT POTENTIAL TRANSFORMERS

A TRANSFORMER is usually designed to take current from the mains at a prescribed electromotive force and frequency, and to deliver current to a receiving circuit at a different prescribed electromotive force.

In the designing of such a transformer there is but one condition which must be met precisely, namely, the ratio of primary to secondary turns must be equal to the ratio between the prescribed primary and secondary voltages. All other points in the design are to a large extent matters of choice guided in a general way by experience.

In designing a transformer, the principal points to strive for are: 1, good insulation; 2, good regulation; 3, high efficiency; 4, small open-circuit current; 5, small rise in temperature; 6, low first cost.

Some of these conditions are opposed to others, as for example high efficiency and low first cost. The allowable temperature rise varies widely with different makers, also the extent of radiating surface required per watt loss per degree rise of temperature varies between extremely wide limits, hence no simple rule can be given governing the matter.

Given the required output of a transformer (rated output which can be satisfactorily delivered to a non-inductive

circuit), frequency, primary and secondary electromotive force, the design of the transformer may be determined as follows:

(A) Flux Linkage

(1) $$E' = \frac{\sqrt{2}\pi N'\phi f}{10^8}.$$

(2) $$\phi N' = \frac{10^8 E'}{\sqrt{2}\pi f} = \frac{22510000\, E'}{f},$$

where ϕ = maximum magnetic flux;
f = frequency in cycles per second;
N' = number of turns in primary;
E' = primary electromotive force;
$\phi N'$ = flux linkages.

(B) Flux and Number of Turns

Either the flux or the number of turns must be assumed. The first assumption will probably give a poorly proportioned design. If so, new assumptions must be made and the design revised, until finally the proper proportions are obtained. This requires both judgment and patience.

Table III gives fair values for the total fluxes of distributed coil lighting and power transformers. Table IV gives a similar set of values for the distributed magnetic circuit type. Both tables are based on a frequency of 60 cycles per second. From Eq. (2) it is seen at once that if the frequency is lower the flux-linkages must be correspondingly larger. Therefore, either the flux or the number or turns or both, must be increased.

TABLE III

Distributer Coil Type

Capacity in Kilowatts.	Flux in Maxwells.	Capacity in Kilowatts.	Flux in Maxwells.
1	180000	30	950000
2	240000	40	1000000
5	400000	50	1050000
10	600000	60	1100000
15	720000	75	1150000
20	840000	100	1200000
25	900000		

TABLE IV

Distributed Magnetic Circuit Type

Capacity in Kilowatts.	Flux in Maxwells.	Capacity in Kilowatts.	Flux in Maxwells.
1	300000	30	1600000
2	400000	40	1670000
5	680000	50	1725000
10	1000000	60	1775000
15	1200000	75	1825000
20	1400000	100	1900000
25	1500000		

(3)
$$N''=\frac{N'}{r},$$

where N'' = number of secondary turns;
r = ratio of transformation.

(C) Area of Magnetic Circuit

$$A_m = \frac{\phi}{(.92)\,(B)} \tag{4}$$

where A_m = area magnetic circuit;
B = flux density.

An allowance of 8 per cent is made for the insulation between the iron laminations making up the core.

For 25-cycle transformers assume a flux density of from 60,000 to 75,000 lines of force per square inch; for 60-cycle transformers from 45,000 to 60,000 lines per square inch; for 125-cycle transformers from 35,000 to 50,000 lines per square inch.

If the magnetic circuit is distributed, A_m is the total average area of the magnetic circuits. The different magnetic circuits are in parallel and each is usually of the same area and length, thus having equal reluctance, if only two magnetic circuits are employed. If there are four magnetic circuits, as in the Westinghouse, General Electric Co., and Western Electric Co. types, the three limbs of the rectangle which are outside the coils have an area about 50 per cent larger than the limb of the rectangle which is inside the coils. Of course, this means a higher magnetic density in these central portions of the iron and that each magnetic circuit must be considered as a compound circuit in calculating the number of ampere turns. Figs. 14 and 15 illustrate these particular types of magnetic circuits. In the General Electric Co. and Western Electric Co. types the four magnetic circuits are combined into one in the center, thus providing one large central core upon which the coils are assembled.

There are various methods of procedure from this point on. In the method about to be outlined by the author

FIG. 28.—Central Cores of Modern Distributed Magnetic Circuit Transformers (Western Electric Co.).

the iron loss is assumed. From the guaranteed efficiencies of various manufacturers one can easily predetermine this loss very closely. In the modern transformer the leakage

is so small that the copper loss practically determines the regulation on non-inductive loads. The core-loss and copper loss practically determine the efficiency. Hence, if the efficiency on a non-inductive load and the regulation are guaranteed, the core loss can be very closely estimated.

FIG. 29.—Magnetic Circuits and Coils of Modern Transformer (Western Electric Co.).

If the regulation of a well-designed transformer is 2 per cent and the efficiency is 96 per cent on a non-inductive load, the core loss will probably be slightly less than 2 per cent $(100-96-2=2)$ of the capacity of the transformer. Table I, Chapter II gives the core losses for a line of transformers made by a reputable manufacturer. Then again in the hand-books and in several of the manufacturing

Fig. 30.—Part of Magnetic Circuit and Coils of Modern Transformer (Western Electric Co.).

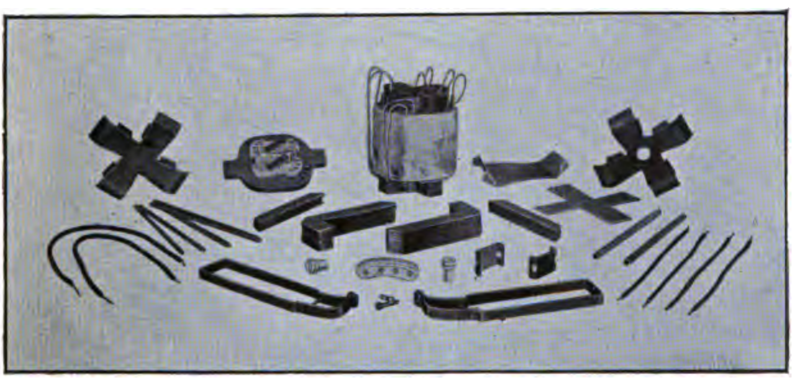


Fig. 31.—Parts of Modern Transformer (Western Electric Co.).

companies' bulletins may be found tables giving the actual iron losses of various-sized transformers up to 50-KW. capacity.

The losses in a transformer of increasing size, assuming the same constants of design, increase only approximately as the *fourth root of the* 3.4 *power of the output.* Therefore, with larger and larger units a point is soon reached where the losses are relatively low and more than satisfying service requirements in this respect. In large transformers of the power class built for use in central stations where the transformers are usually fully loaded nearly all the time, there is not so much of a demand to keep down the iron losses, therefore no demand for lower iron losses than copper losses. In transformers of this class the losses are usually made about equal.

(D) Volume of Iron

(5) $$W_h=\frac{\eta f V B^{1.6}}{10^7} \quad \text{(Steinmetz).}$$

(6) $$W_e=\frac{1.645\ d^2 f^2 B^2 V}{10^{11}} \quad \text{(Steinmetz).}$$

(7) $$W_c=W_h+W_e.$$

(8) $$W_c=\frac{\eta f V B^{1.6}}{10^7}+\frac{1.645\ d^2 f^2 B^2 V}{10^{11}}$$

$$=\frac{Vf(10^4\eta B^{1.6}+1.645\ d^2 f B^2)}{10^{11}}$$

(9) $$V=\frac{10^{11}W_c}{f(10^4\eta B^{1.6}+1.645\ d^2 f B^2)},$$

where W_h = hysteresis loss in watts;
W_e = eddy current loss in watts;
W_c = total core loss in watts;
V = volume of iron in cubic centimeters;
f = frequency in cycles per second;
η = coefficient of hysteresis;
B = number of lines of force per square centimeter;
d = thickness of iron laminations in centimeters.

0.0012 is a fair value for η. The thickness of iron laminations used in most transformers is about 14 mils, that is 0.014 in.

(E) Length of Magnetic Circuit

(10) $$L_m = \frac{V}{A_m},$$

where L_m = length of magnetic circuit in centimeters;
A_m = area of magnetic circuit in square centimeters;
V = volume of magnetic circuit in cubic centimeters.

If the magnetic circuit is distributed, L_m will be the length of each one of the parallel circuits.

(F) Area of Conductors

In a well-ventilated transformer it is usually necessary to provide 1000 to 1200 circular mils per ampere in the high-tension winding and from 1200 to 1500 circular mils per ampere in the low-tension winding.

(11) $$I' = \frac{\text{Watt capacity}}{E'},$$

where I' = primary current (for purpose of design);
E' = primary electromotive force.

$$I'' = \frac{\text{Watt capacity}}{E''}, \tag{12}$$

where I'' = secondary current;
E'' = secondary electromotive force.

(G) Space Occupied by Core and Windings

Lay out a magnetic circuit on the drawing board which will have approximately the predetermined area and volume and which will accommodate the windings in the space which is available. A good idea of the relative dimensions of the magnetic circuit may be obtained by examining the illustrations in Chapter IV. In determining the space occupied by the coils proper allowance must be made for isulation and for ventilating ducts.

(H) Number of Secondary Turns

$$N'' = \frac{N'E''}{E'}, \tag{13}$$

where N'' = number of secondary turns;
N' = number of primary turns;
E'' = secondary electromotive force;
E' = primary electromotive force.

The primary and secondary coils should be split up into at least two coils to allow connecting in series or multiple for different circuits.

(I) Weight and Resistance of Conductor

The average length per turn and the total length and total weight of copper in each coil may now be readily determined.

(J) Losses

The copper loss in the primary may be obtained by the Eq.;

(14) $$W' = (I')^2(R'),$$

where W' = copper loss in primary;
I' = primary current;
R' = resistance of primary.

The copper loss in the secondary will be similarly:

(15) $$W'' = (I'')^2R'',$$

where W'' = copper loss in the secondary;
I'' = secondary current;
R'' = resistance of secondary.

The hysteresis and eddy current losses may be obtained by Formulas (5) and (6). These losses will of course be about as expected, since the basis of the design in the beginning was the amount of these losses.

(K) No-load Primary Current

The no-load primary current I_0' is the resultant of the iron loss component I_w' and the magnetizing component I_m'.

(16) $$I_0' = \sqrt{(I_m')^2 + (I_w')^2}.$$

(17) $$I_w' = \frac{W_c}{E},$$

where W_c = core loss in watts;
E' = primary voltage

(18) $$I_m' = \frac{10L_m\phi}{4\pi N'A\eta\sqrt{2}} = \frac{.5627\,BL_m}{N'\eta},$$

where B = flux density;

N' = number of primary turns;

η = permeability of the magnetic circuit at the density B. (See table II, Chapter II).

L_m = length of magnetic circuit.

In order to determine the primary current at various

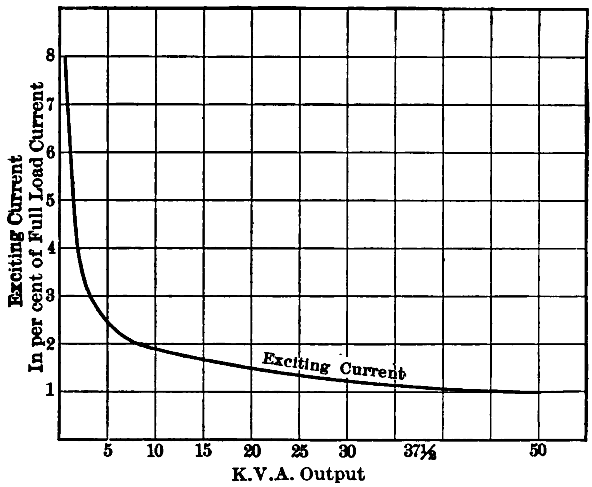


FIG. 32.—Exciting Current in Transformers of Recent Design (N.E.L.A. Proceedings, 1909, Vol. I).

non-inductive loads, I'_w is added directly to I' and I'_m to I' at right angles; I' being the current which would flow in the primary if the efficiency were 100 per cent.

The no-load primary current is exceedingly small in a well-designed transformer, hence the error made by obtaining the primary current by dividing the watt capacity by the primary electromotive force is negligible.

(L) Leakage Flux

The amount of magnetic leakage in a transformer depends very largely upon the separation of the primary and secondary windings. The leakage would be a minimum if each primary turn were opposed by a secondary turn lying in exactly the same position. This is of course

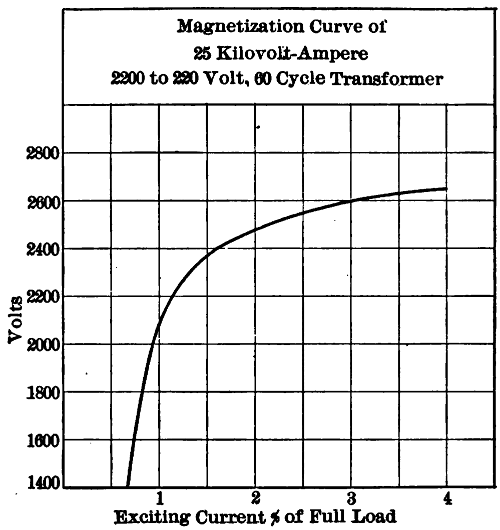


FIG. 33.—(N.E.L.A. Proceedings, 1909, Vol. I.)

impossible and magnetic leakage is present to just such an extent as this condition is not attained. Some writers have attempted to treat this problem mathematically. Such treatments are very difficult, and are very approximate even at their best.

Although a number of theoretical equations are available

for determining the magnetic leakage reactance of a transformer, only those that are based on empirical constants obtained from the exact type of transformer under consideration give results that conform with those obtained by test. The author believes that it is as useless to attempt to calculate the leakage in a transformer as it is of a direct-current dynamo. Practically every dynamo designer takes his leakage coefficient from a table based on his own or others, experience. Table V has been prepared from the results of data gathered from actual tests, and a number of calculations made by the author on several different transformers. Leakage may be kept down by so interspacing the primary and secondary coils as to provide as many leakage surfaces as possible.

Dr. A.S. McAllister has given some "empirical" formulas in the Standard Hand-book on p. 237 that seem to possess considerable merit both from the standpoint of simplicity and comparative accuracy.

(M) Regulation

Magnetic leakage appears externally as an inductive reactance in both the primary and secondary coil. If all the lines which fail to pass through the secondary coils cut all the primary turns, it could be stated that the magnetic leakage reactance varies directly as the square of the primary turns; this assumption which will be made is therefore only approximately true. The error however is very small under normal conditions and furthermore is on the safe side.

The leakage coefficient given in Table V is the constant by which the total maximum flux in the transformer is

TABLE V

LEAKAGE COEFFICIENTS FOR MODERN LIGHTING TRANSFORMERS

(*A*) *Single Magnetic Circuit with Subdivided Coils. Coils on Rectangular Core*

No. of Subdivisions of primary coil (interleaved with secondary).	No. of Subdivisions of secondary coil (interleaved with primary).	Leakage coefficient.
2	2	0.05
3	3	0.03
4	4	0.02
5	5	0.01
6	6	0.006
(*B*) *Single Magnetic Circuit with Coaxial Coils on Rectangular Core, (Distributed Coil Type.)*		
2	2	0.025
3	3	0.018
4	4	0.012
5	5	0.009
(*C*) *Two Magnetic Circuits in Parallel. (Shell Type.)*		
1	2	0.05
2	1	0.05
2	2	0.03
3	3	0.02
4	4	0.015
5	5	0.01
(*D*) *Four Magnetic Circuits in Parallel. (Distributed Iron.)*		
1	1	0.04
2	1	0.023
1	2	0.023
2	2	0.019
2	3	0.015
3	2	0.015
3	3	0.010

multiplied in order to get the flux which is to be substituted in the formula,

$$L_T = \frac{N'\phi'}{10^8 I'_{\text{max.}}}$$

in order to get the inductance which when multiplied by the quantity $2\pi f$ will give X_T where X_T is the total leakage reactance of the transformer measured on the primary coil. If X_p is the actual leakage reactance of the primary, X_s the actual leakage reactance of the secondary, and r the ratio of transformation; then X_p and X_s may be replaced by an equivalent reactance X_T connected in series with the primary coil where,

$$X_T = 2\pi f L_T,$$

and

$$L_T = \frac{N'\phi'}{10^8 I'_{\text{max.}}}$$

where N' = number of primary turns;

$I'_{\text{max.}}$ = primary current in amperes (maximum);

ϕ' = leakage flux as obtained by multiplying the total maximum flux by the coefficient given in Table V;

f = frequency in cycles per second.

The fact that the effect of magnetic leakage in a transformer is equivalent to an inductance L_T connected in series with the primary is illustrated very clearly by Franklin & Williamson in their book on Alternating Currents, pp. 131 and 132.

We are now ready to construct the complete vector diagrams of electromotive forces and currents in a transformer corresponding to the following arrangement:

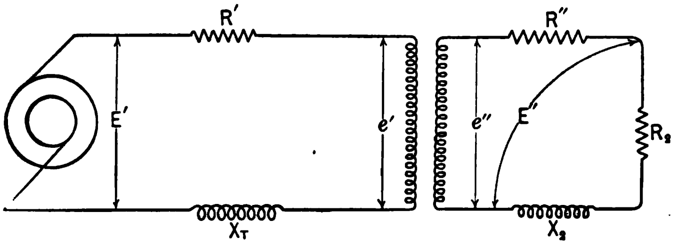


FIG. 34.

Imagine the transformer itself to be an "ideal" one, i.e., as possessing no core losses, no ohmic resistances in the windings, and no magnetic leakage. The ohmic resistance of primary coil is replaced by an equal resistance R' outside the transformer. The effect of the leakage is taken care of by means of the reactance X_T also outside of the transformer and in series with the primary coil. R'' is equal to the resistance of the secondary, and X_2 and R_2 represent the reactance and resistance respectively of the load. The current in the secondary I'' is,

$$I''=\frac{E''}{\sqrt{R_2{}^2+X_2{}^2}}.$$

The angle α is determined as follows:

$$\alpha=\tan^{-1}\frac{X_2}{R_2}.$$

From the above diagram it is seen that the impressed e.m.f. E' is reduced by an amount $I'R'$ in phase with I' plus $I'X_T$ at right angles to I'. This leaves the e.m.f.

e' to be impressed upon our ideal transformer. The e.m.f. e'' available at the secondary terminals of this ideal transformer is e'/r, where r is the ratio of transformation. This is still further reduced by an amount $I''R''$ in phase with

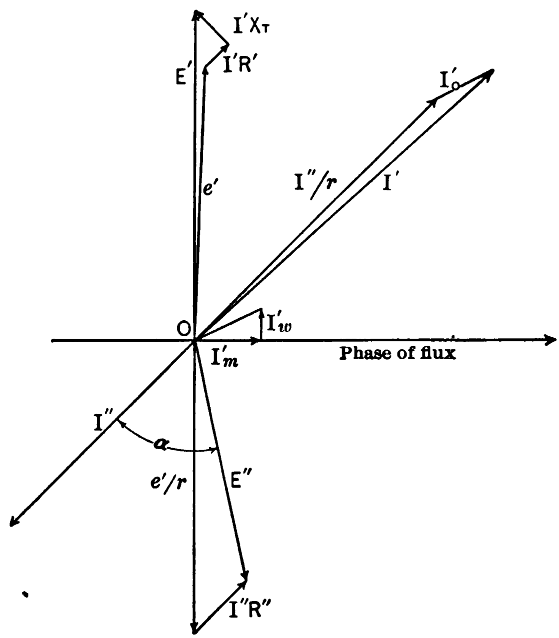


FIG. 34*a*.

I'' leaving the e.m.f. E'' available to be applied to our load. The regulation in per cent is, therefore,

$$\text{Regulation} = \left(\frac{E'/r - E''}{E''}\right)100.$$

The regulation is ordinarily calculated at 100 per cent power factor (secondary load) and at 80 per cent power factor.

(N) Efficiency

The efficiency for non-inductive load is given by the formula:

$$\text{(19)} \qquad \text{Efficiency} = \frac{E''I''}{E''I''+I'^2R'+I''^2R''+W_c}.$$

The all-day efficiency is usually calculated on the basis of full-load for five hours and no load for nineteen hours. It is thus given by the formula:

$$\text{(20)} \qquad \text{Efficiency} = \frac{5E''I''}{5(E''I''+I'^2R'+I''^2R'')+24W_c}.$$

(O) Case

In designing a case, the principal points to keep in mind are, strength for handling, provision for securing coils in position, accessibility for inspection and repairs, proper insulation of leads where they pass through the case and large radiating surface with small weight. There should be provided approximately three square inches of radiating surface per watt of loss for oil-cooled transformers and six for air-cooled transformers. In the larger sizes it will be found necessary to corrugate the case in order to obtain sufficient radiating surface.

FIG. 35.—Modern Transformer Removed from Case (Western Electric Co.).

FIG. 36.—Showing Case and Method of Bringing Out Leads (Western Electric Co.).

FIG. 37.—Showing Case of Large Transformer (Western Electric Co.).

FIG. 38.—Showing Case of Modern Transformer (Westinghouse Co.).

FIG. 39.—Looking Down into Distributed Magnetic Circuit Transformer (Westinghouse Co.).

FIG. 40.—Distributed Magnetic Circuit Transformer (Western Electric Co.).

Fig. 41.—Transformer for Use on Pole (Westinghouse Co.).

Fig. 42.—Transformer for Use on Pole (Western Electric Co.).

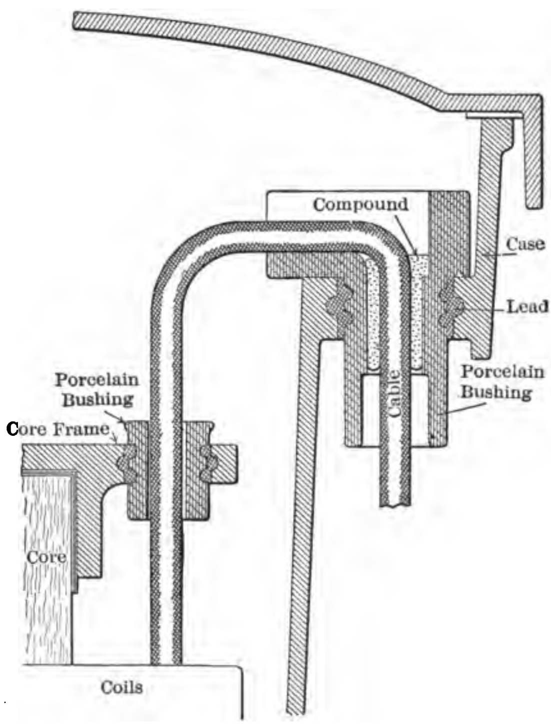


FIG. 43.—Illustrating Method of Bringing Out Secondary Leads (Wagner).

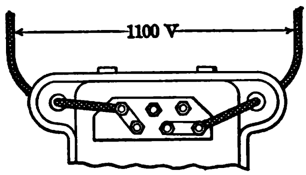
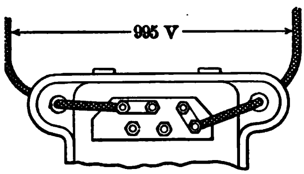
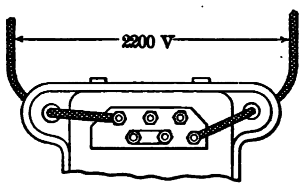
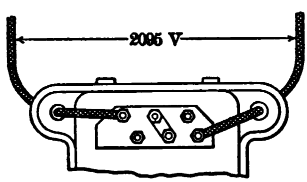
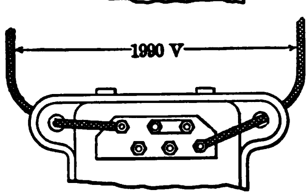
Arrangement of Links on the Connection Board.	Primary Coils will be Connected in	For Circuit Voltage Normal at	Ratio of Transformation at no Load	
			with Secondary Coils in Multiple.	with Secondary Coils in Series.
	Multiple	1100	10 : 1	5 : 1
	Multiple	1100	9.05 : 1	4.52 : 1
	Series	2200	20 : 1	10 : 1
	Series	2200	19.05 : 1	9.5 : 1
	Series	2200	18.1 : 1	9.05 : 1

FIG. 44.— Illustrating Primary Terminal Block and Connections (Wagner).

CHAPTER IV

The illustrations shown in this chapter are from transformer designs worked out by senior students in electrical engineering under the guidance of the author and using the method of design outlined in the previous chapter. The first four of the designs are transformers of the same rating, transformation, ratio, etc., but of different types.

No. 7 is a 4-KW. transformer designed and built by students in the electrical engineering laboratory of the University of Minnesota. The ratio of transformation is one to one, or one to two. The voltage may be 110 or 220. Ten-volt taps and Scott connections are provided. These transformers are mounted on ball-bearing casters and are placed in the laboratory for the elementary transformer tests. They make an excellent type for this class of work.

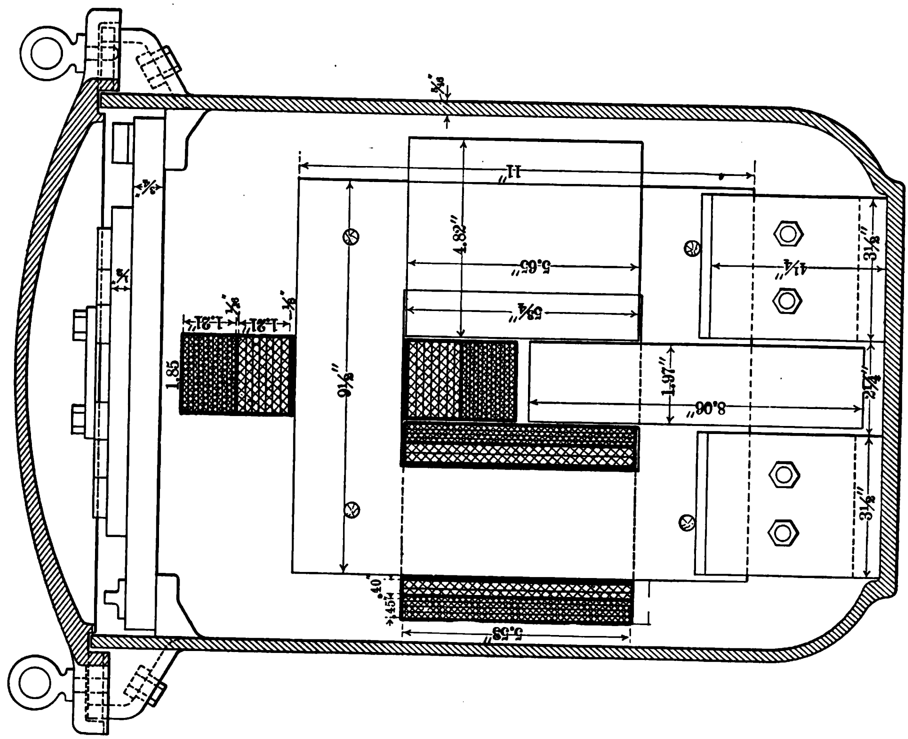
No. 11 is a 7-KW. welding transformer designed and built by students for use in the electrical laboratory of the University of Minnesota. It provides an excellent source of very large current.

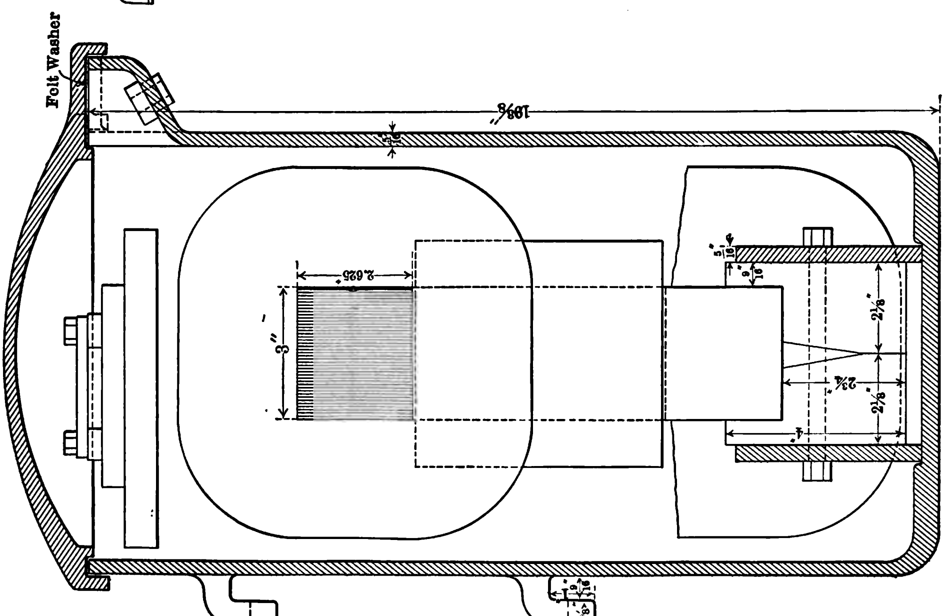
DESIGN No. 1

Type	Distributed coil
Capacity	5000 watts
Primary voltage	2200/1100
Secondary voltage	220/110
Frequency	60 cycles per second
Full load efficiency	96.2
All day efficiency	91.2
Copper loss	117 watts
Hysteresis loss	58 watts
Eddy current loss	17 watts
Weight of copper	67 pounds
Weight of iron core	51 pounds

Windings.	Low Tension	High Tension.
Number of coils	4	4
Turns per coil	54	540
Total number of turns	216	2160
Size of wire	$\frac{3}{16}'' \times \frac{3}{16}''$	No. 15
Length of wire in feet	262	3388
Resistance at 75° F	.085	13.7

DESIGN No. 1—*Continued*





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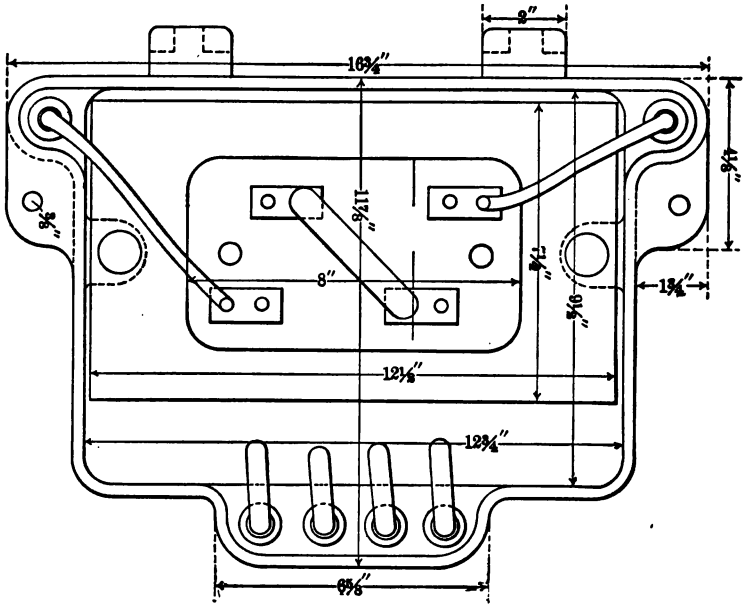
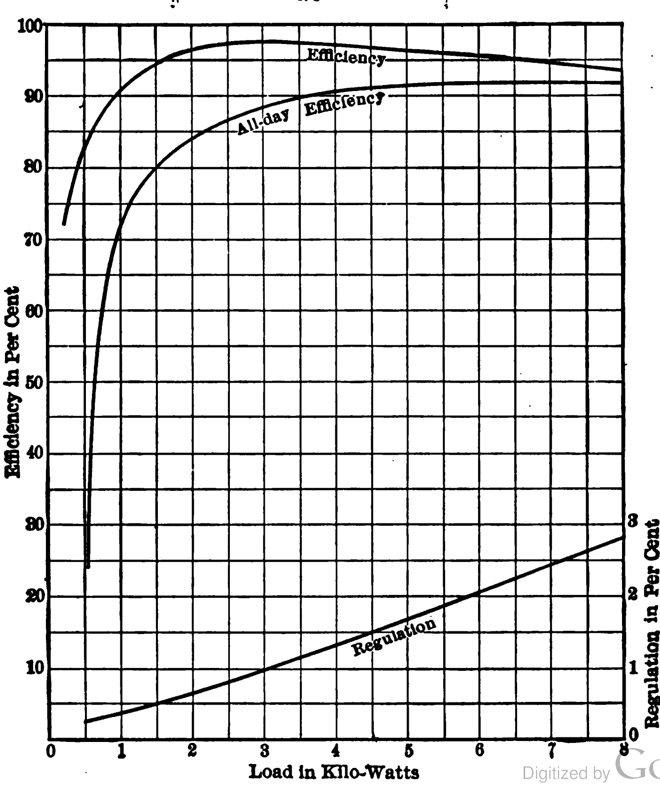


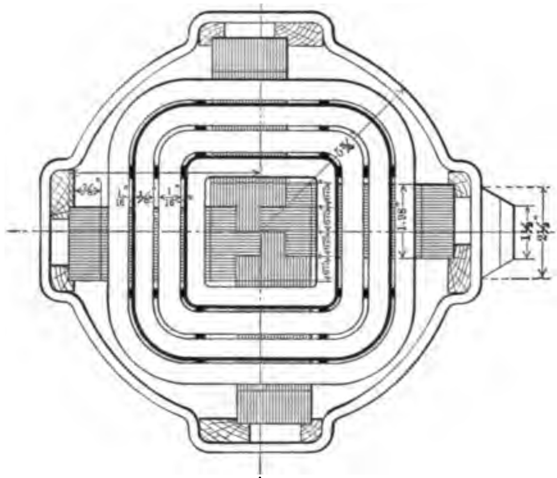


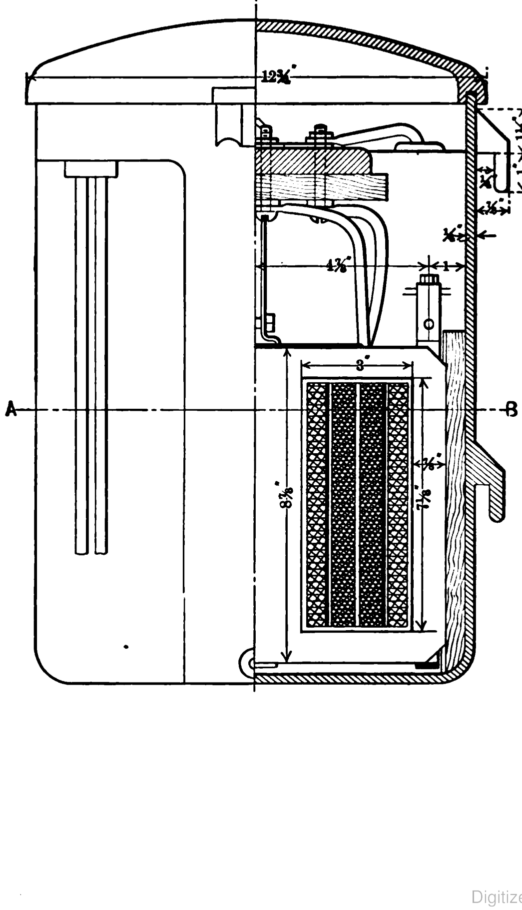
DESIGN No. 2

Type	Distributed iron
Capacity	5000 watts
Primary voltage	2200/1100
Secondary voltage	220/110
Frequency	60 cycles per second
Full load efficiency	95.3%
All day efficiency	91.4%
Copper loss	161 watts
Hysteresis loss	50 watts
Eddy current loss	15 watts

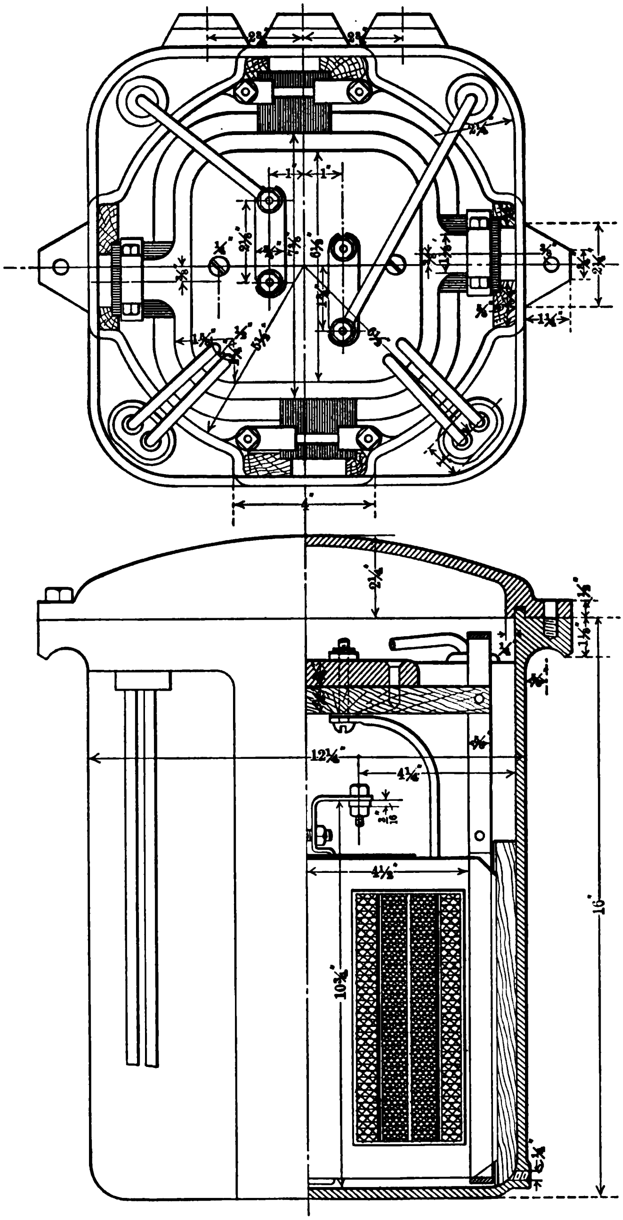
Windings.	Low Tension.	High Tension.
Number of coils	2	2
Size of wire	No. 6	No. 16
Turns per coil	115	1150
Total number of turns	230	2300
Resistance at 50° C.	0.157	16

DESIGN No. 2—*Continued*

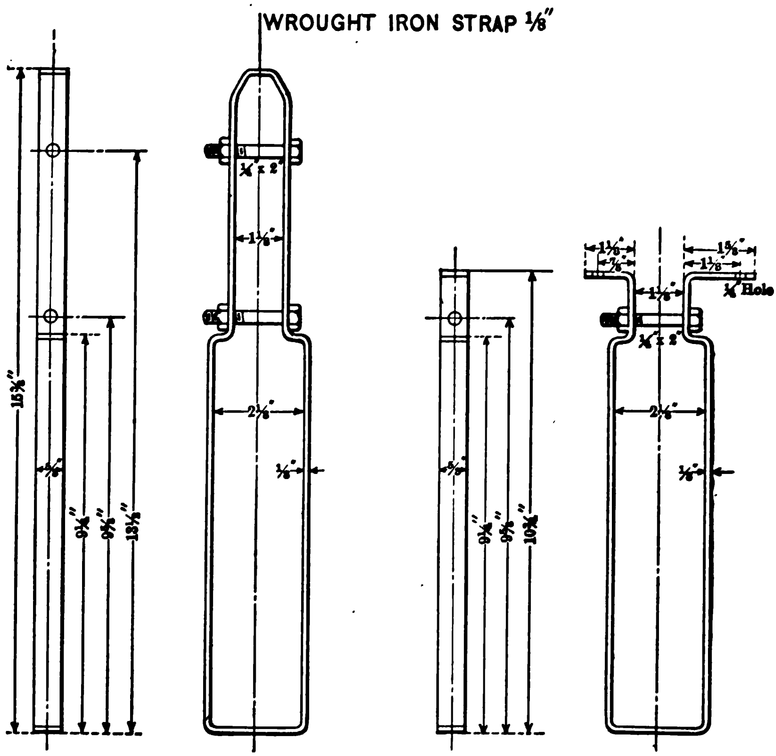




DESIGN No. 2—*Continued*

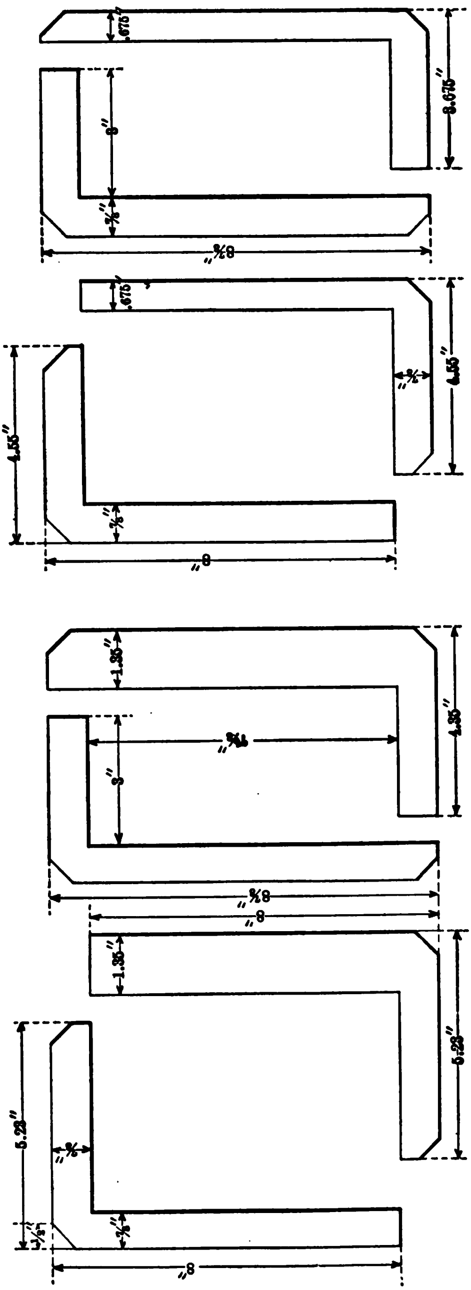


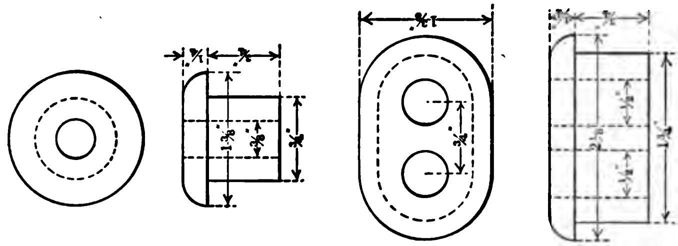
DESIGN No. 2—*Continued*



DESIGN No. 2—*Continued*

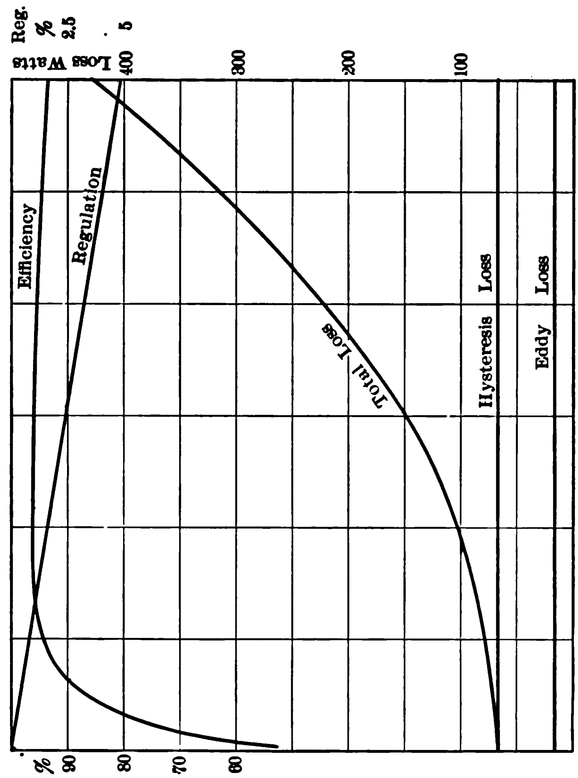
SHEET STEEL CORE STAMPINGS .014"





PORCELAIN TUBES

DESIGN No. 2.—*Continued*

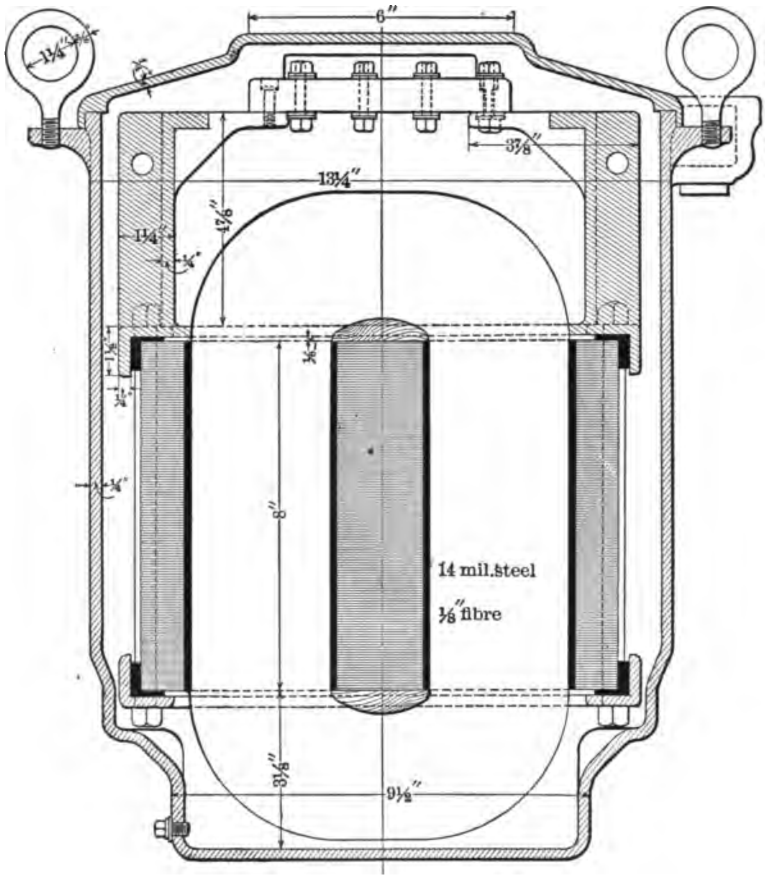


DESIGN No. 3

Type	Distributed iron
Capacity	5000 watts
Primary voltage	2200/1100
Secondary voltage	220/110
Frequency	60 cycles per second
Full load efficiency	96.8%
All day efficiency	91.8%
Copper loss	97.5 watts
Hysteresis loss	54.5 watts
Eddy current losses	17.5 watts
Total losses	169.5 watts

Windings.	Low Tension.	High Tension.
Number of coils	4	4
Turns per coil	48	480
Total number of turns	192	1920
Size of wire	18″×18″	No. 15
Resistance	0.129 ohms	5.08

DESIGN No. 3—*Continued*



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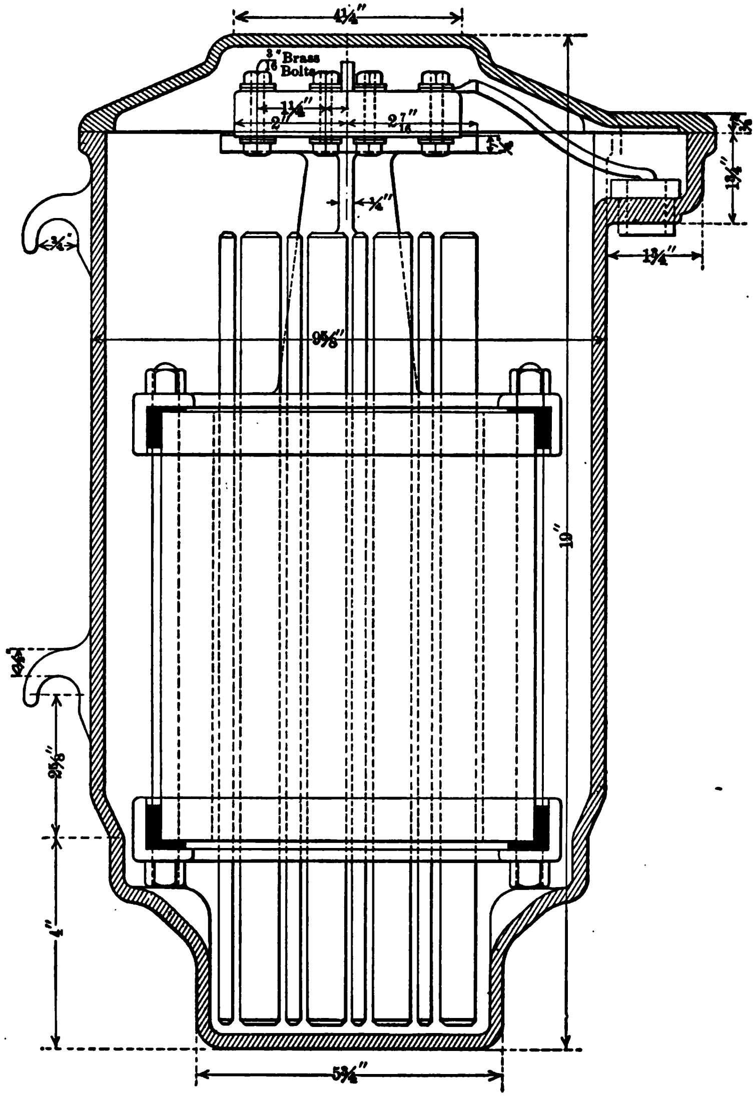

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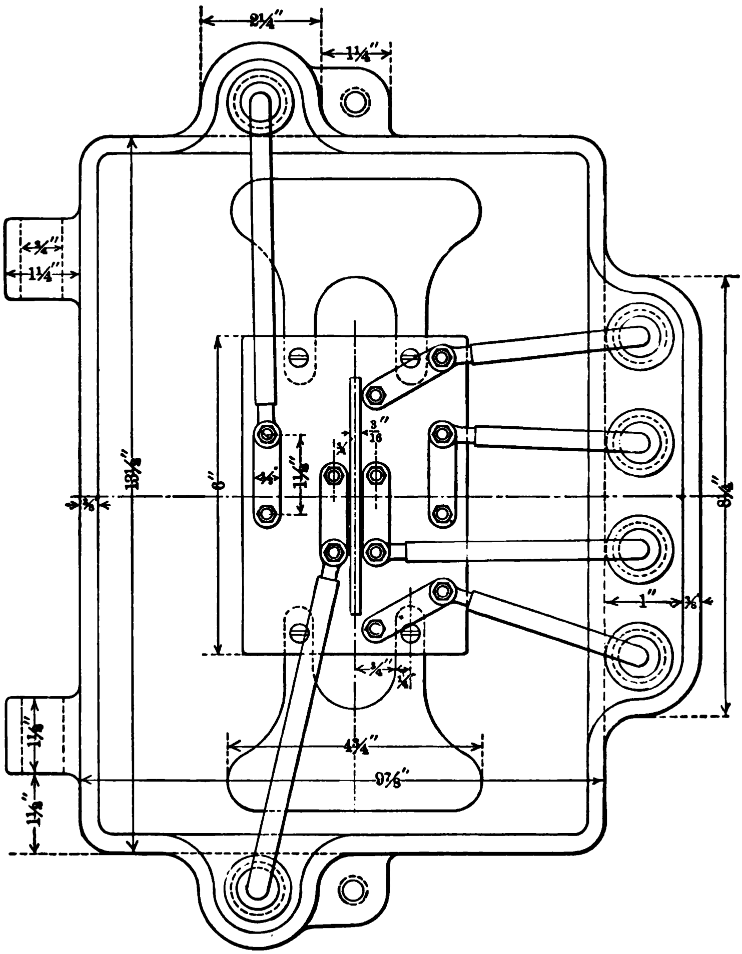

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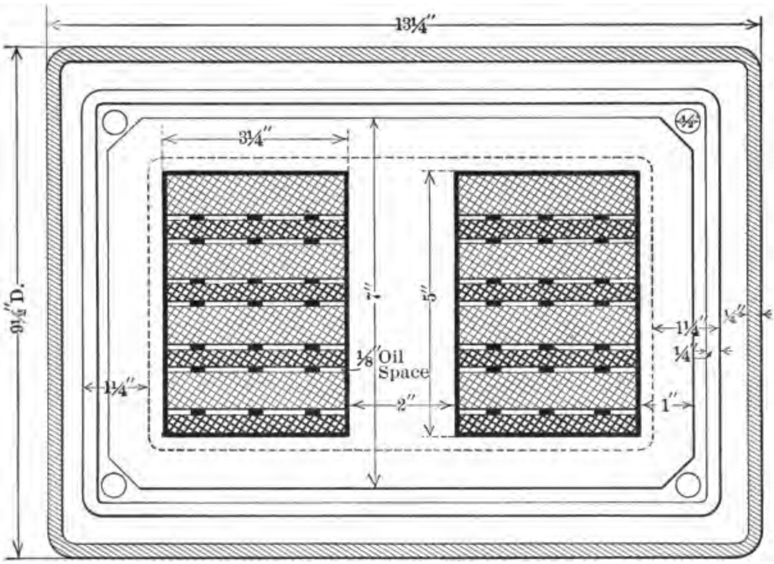
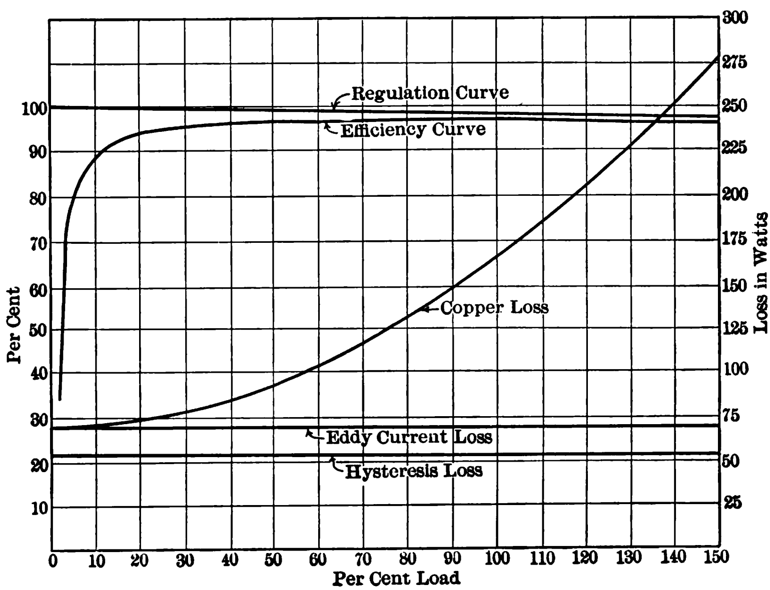


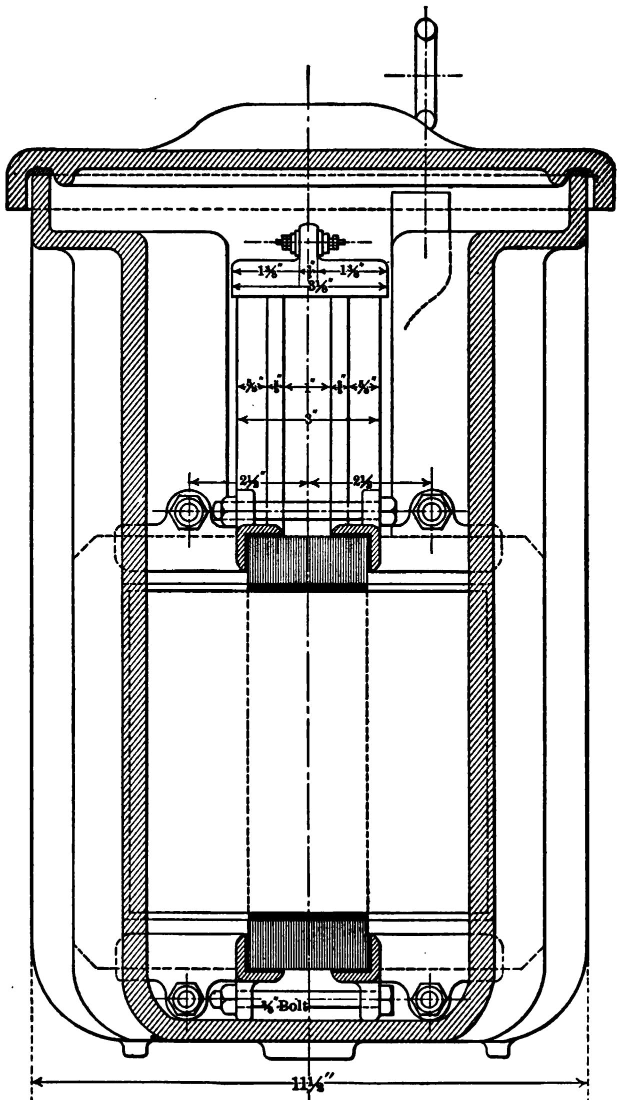


DESIGN No. 4

Type	Distributed iron
Capacity	5000 watts
Primary voltage	2200/1100
Secondary voltage	220/110
Frequency	60 cycles per second
Full load efficiency	96.8%
All day efficiency	93.5 watts
Copper loss	53.8 watts
Hysteresis loss	16 watts
Eddy current loss	

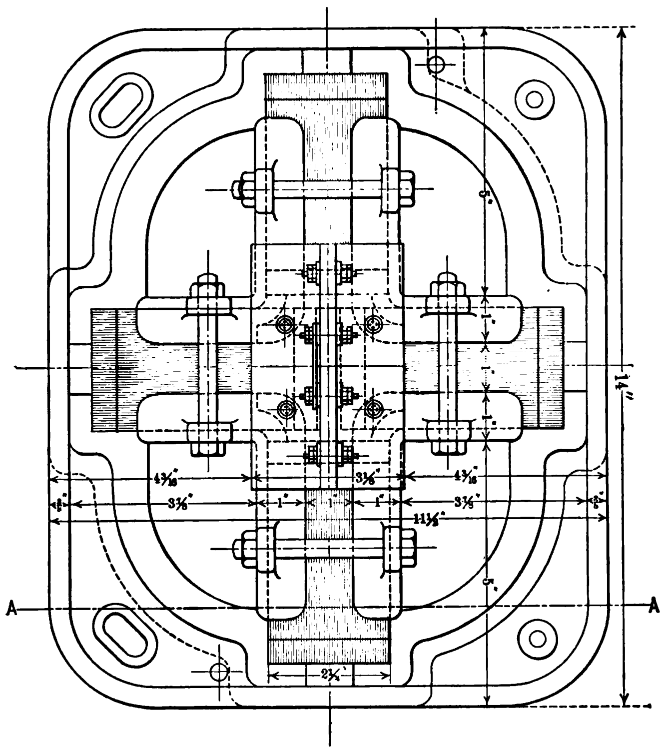
Windings.	Low Tension	High Tension.
Number of coils	2	2
Number of turns per coil	99	990
Total number of turns	198	1980
Size of wire	.110 × .188	No. 16
Resistance at 80° C	.0612	11.67

DESIGN No. 4—*Continued*



SECTION AA

DESIGN No. 4—*Continued*



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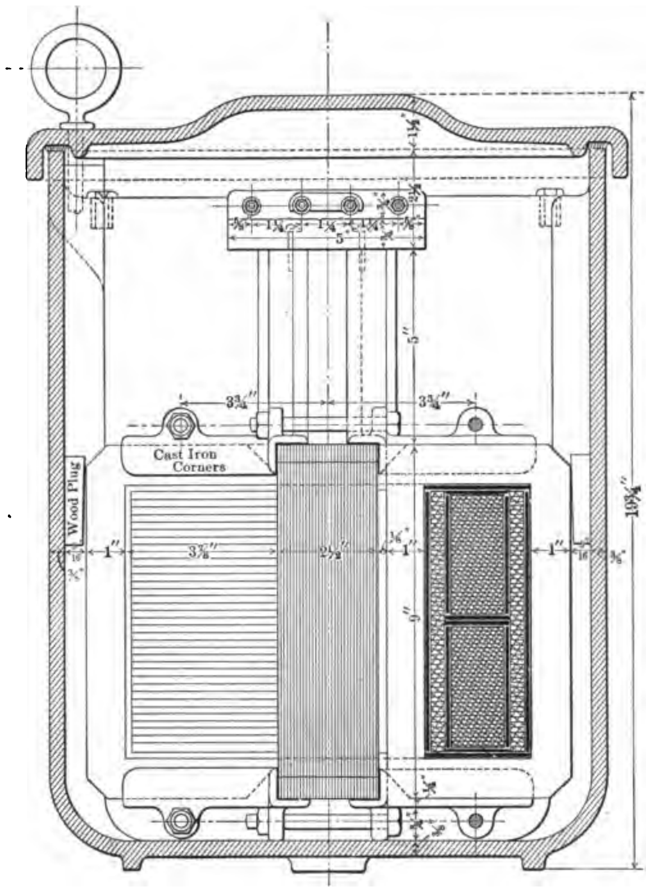
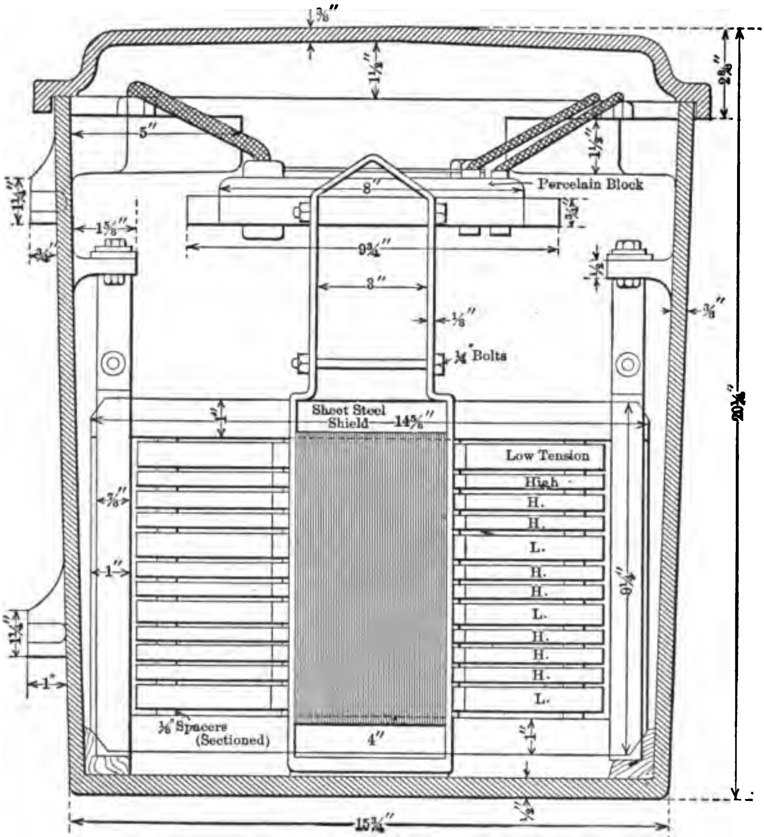


DESIGN No. 5

Type	Distributed iron
Capacity	10,000 watts
Primary voltage	2200/1100
Secondary voltage	220/110
Frequency	60 cycles per second
Full load efficiency	96.7%
All day efficiency	92.3%
Copper loss	228.4 watts
Total core loss	130 watts

Windings.	Low Tension.	High Tension.
Number of coils	4	4
Turns per coil	30	150
Total number of turns	120	1200
Size of wire	$\frac{7}{64}'' \times \frac{1}{2}''$	$\frac{7}{64}'' \times \frac{3}{8}''$
Resistance at 50° C.	.0545	5.45

DESIGN No. 5—*Continued*



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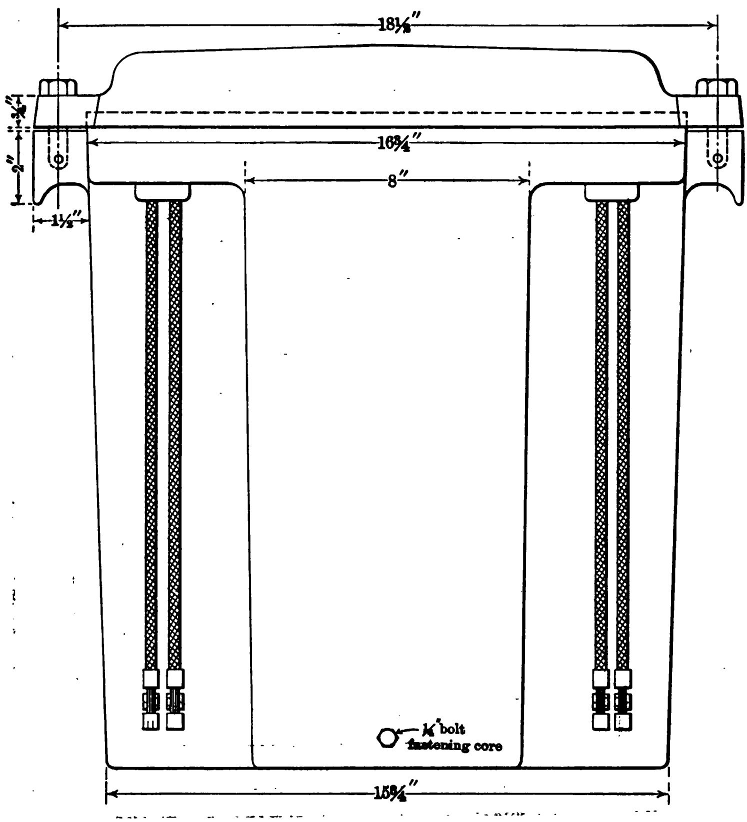

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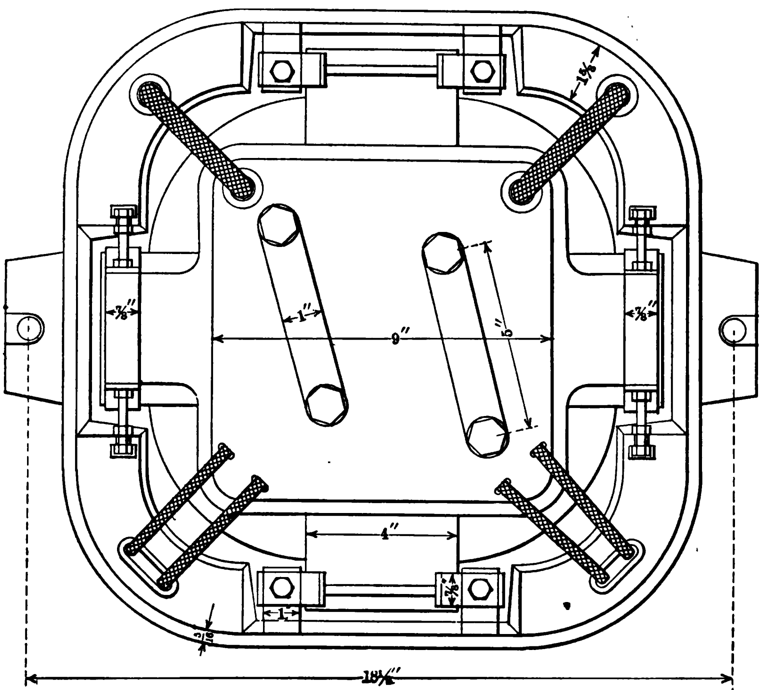

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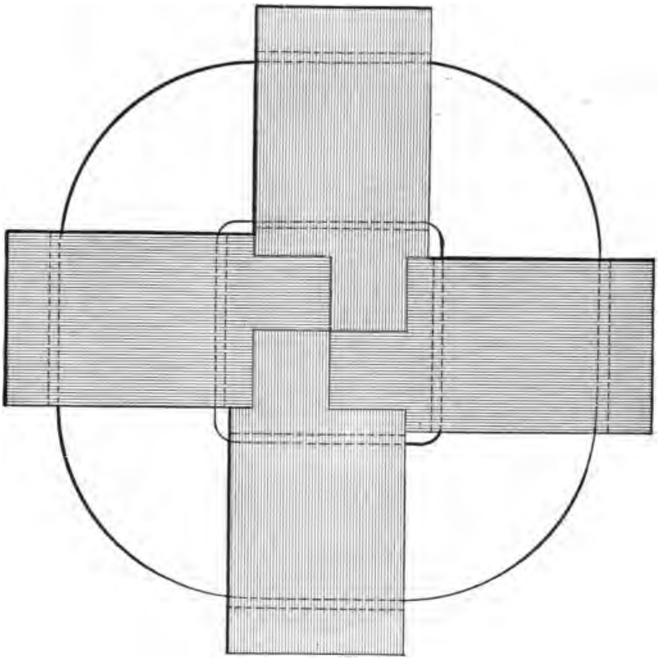
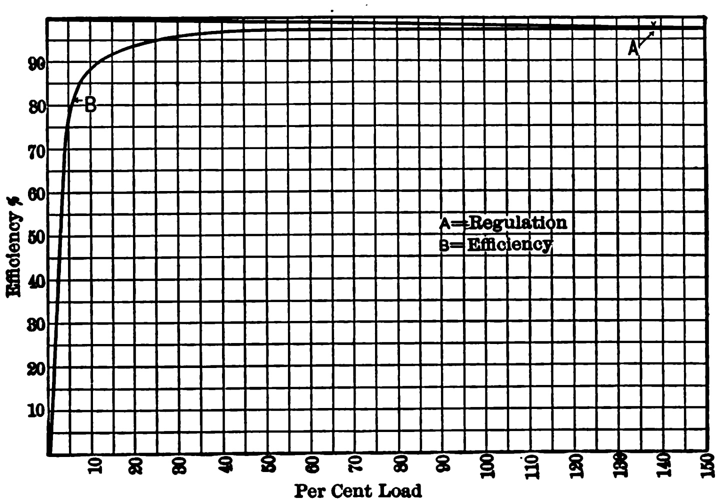


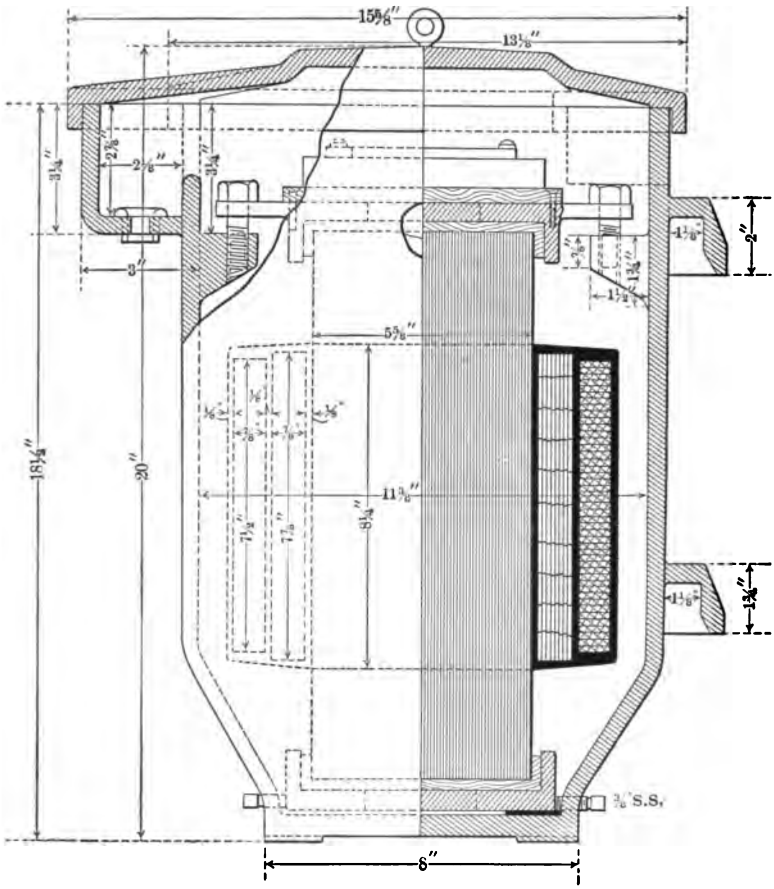


DESIGN No. 6

Type	Distributed coil (core)
Capacity	15,000 watts
Primary voltage	4400/2200
Secondary voltage	440/220
Frequency	60 cycles per second
Full load efficiency	96.8%
All day efficiency	92.6%
Copper loss	285 watts
Hysteresis loss	142.6 watts
Eddy current loss	42.3 watts

Windings.	Low Tension.	High Tension.
Number of coils	2	2
Turns per coil	99	990
Total number of turns	198	1980
Size of wire	$\frac{1}{16}'' \times \frac{3}{8}''$	No. 14
Magnetizing current	....	.0031 ampere
Resistance at 50° C	.081	13.7

DESIGN No. 6—*Continued*



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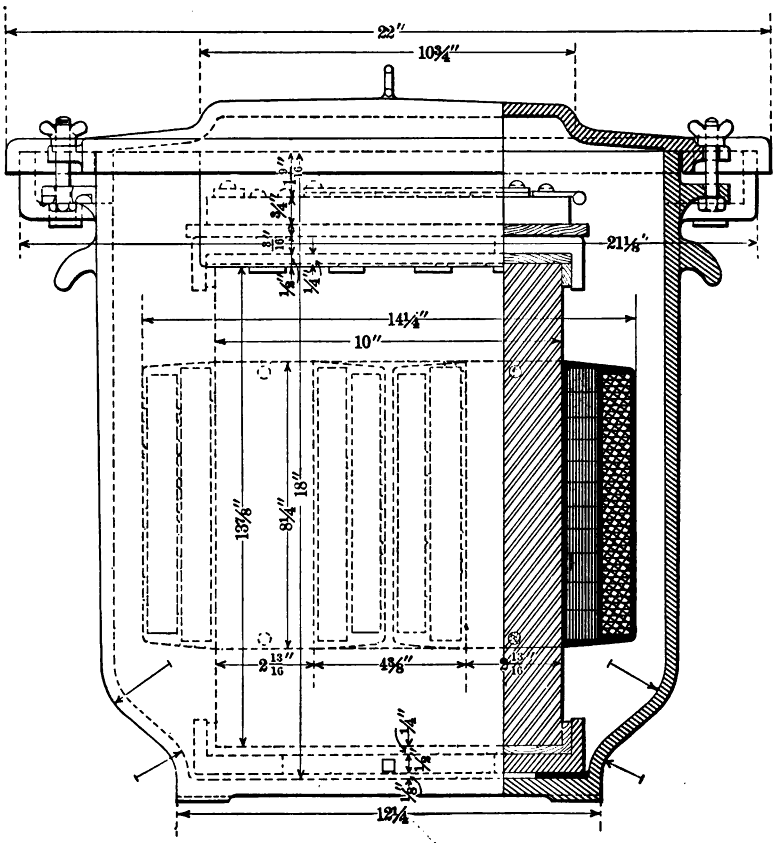

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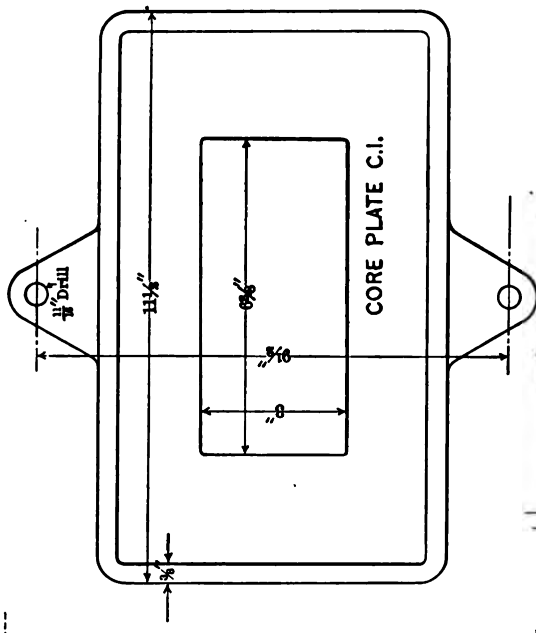

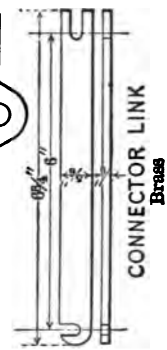

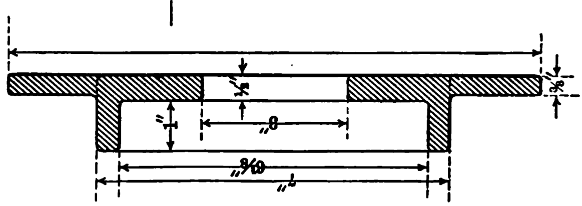

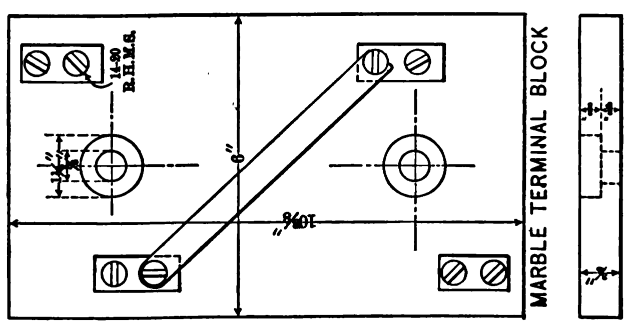

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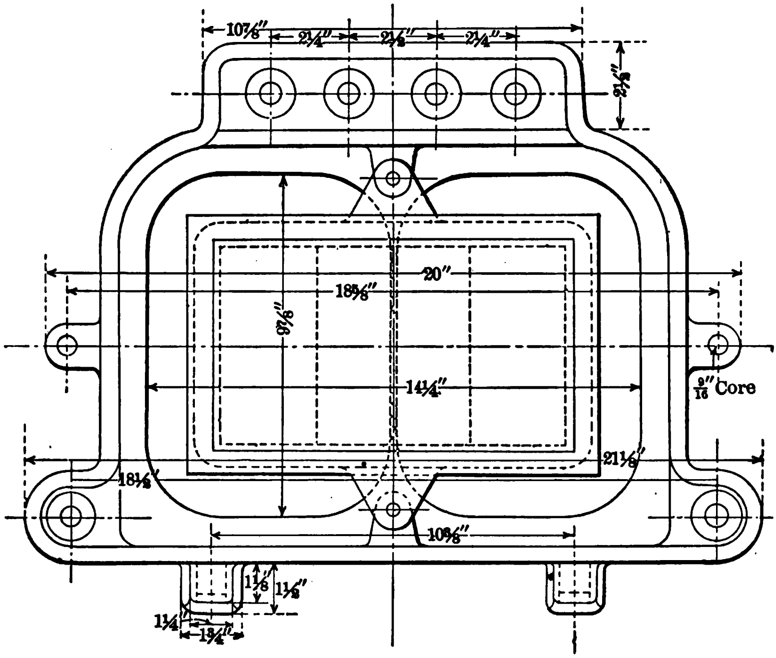
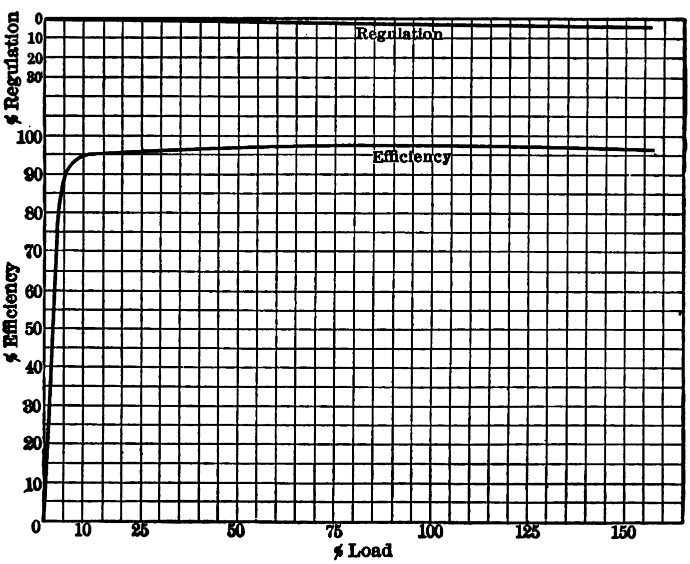




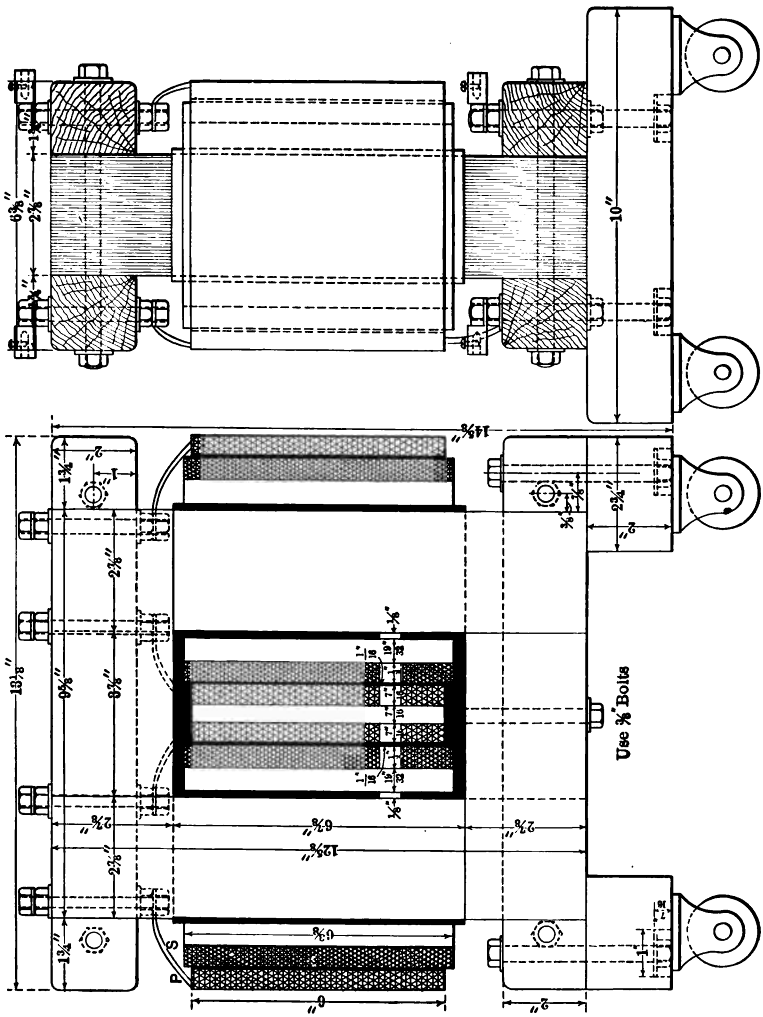
DESIGN No. 7

Transformer for Laboratory Use.

Type	Distributed iron (core)
Capacity	4000 watts
Primary voltage	220/110
Secondary voltage	220/110/95
Copper loss	120 watts
Core loss	100 watts
Weight of copper	42.5 pounds
Weight of iron core	70.5 pounds
Thickness of laminations	.025 inch
Regulation	3.4%
Full load efficiency	94.5%

Windings.	Primary.	Secondary.
Number of coils	2	2
Turns per coil	108	54
Size wire	No. 6 B. & S.	No. 4 B. & S.
c. m. per ampere	1440	1150

DESIGN No. 7—*Continued*



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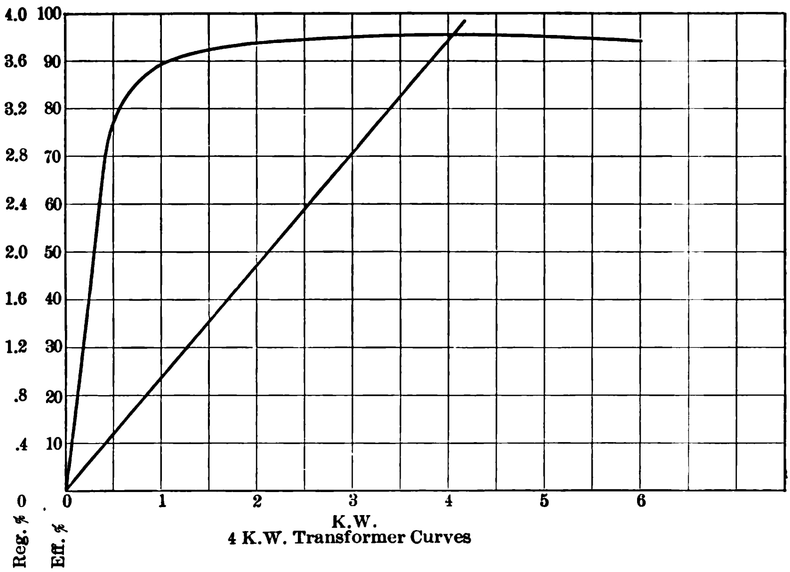
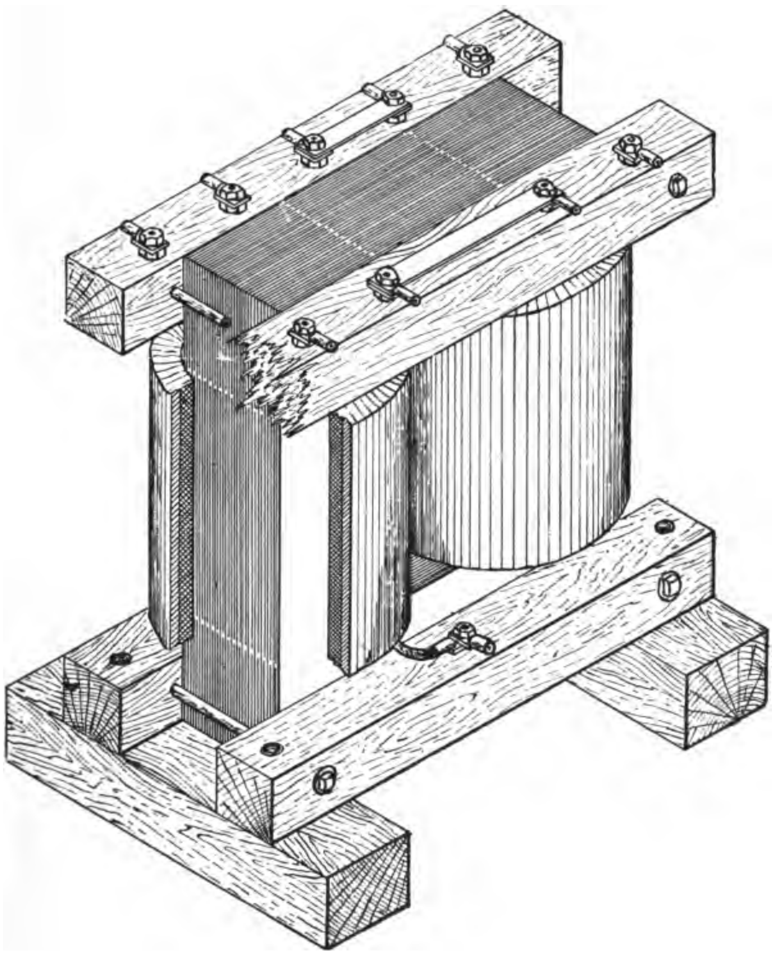


4 K.W. Transformer Curves

DESIGN No. 7—*Continued*



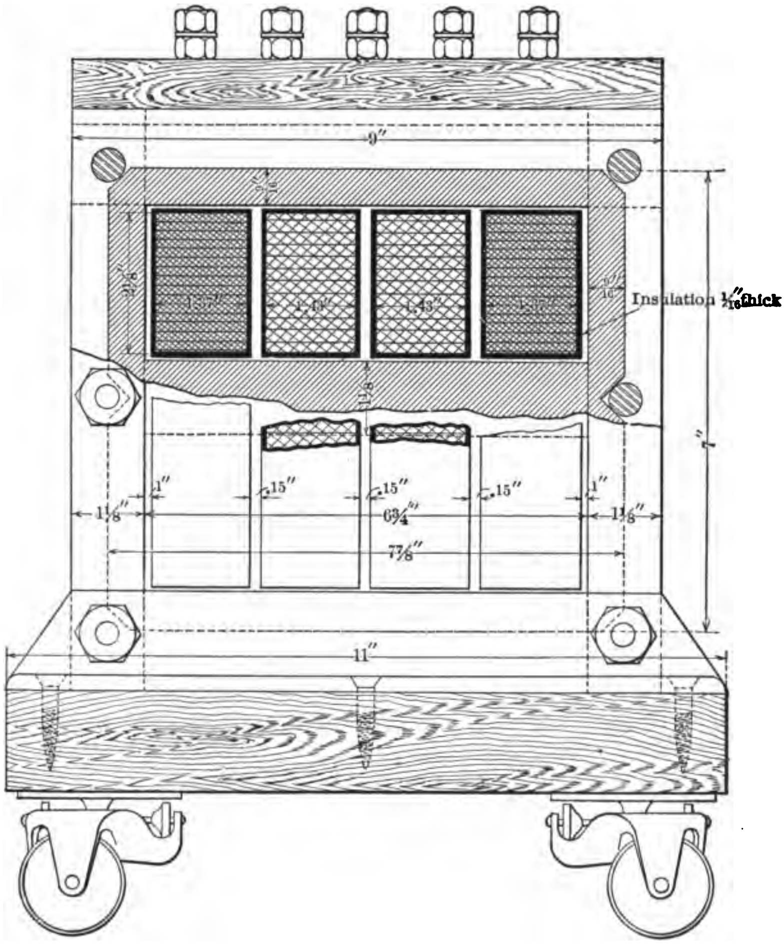
DESIGN No. 8

Transformer for Laboratory Use

Type	Distributed iron (shell)
Capacity	5000 watts
Primary voltage	2200/1100
Secondary voltage	220/110
Frequency	60 cycles per second
Full load efficiency	96.5%
All day efficiency	91.9%
Copper loss	120 watts
Hysteresis loss	49.18 watts
Eddy current loss	15.82 watts

Windings.	Low Tension.	High Tension.
Number of coils	2	2
Turns per coil	95	950
Total number of turns	190	1900
Size of wire	No. 5	No. 16
Resistance at 80° C.	.0736	15.016

DESIGN No. 8—*Continued*



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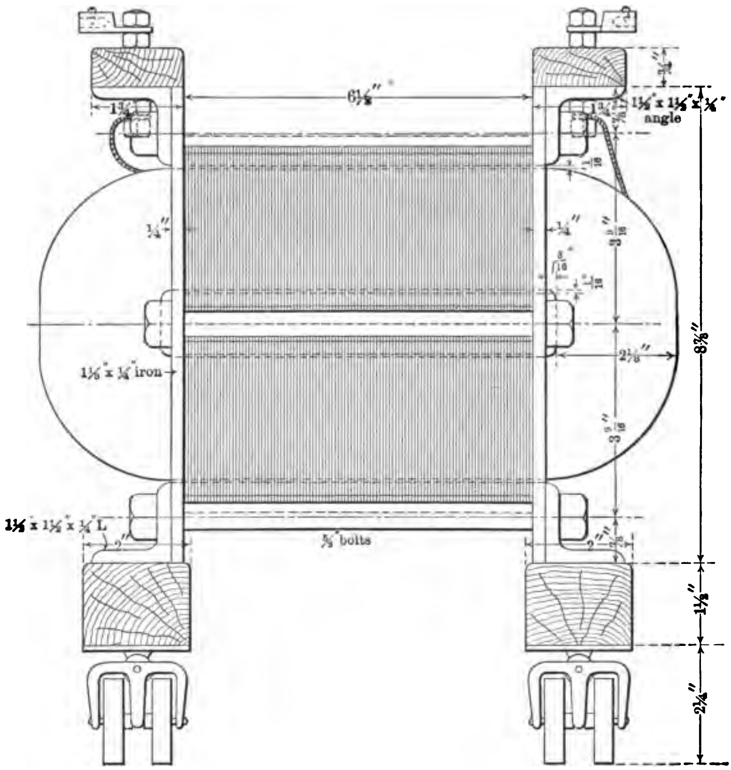

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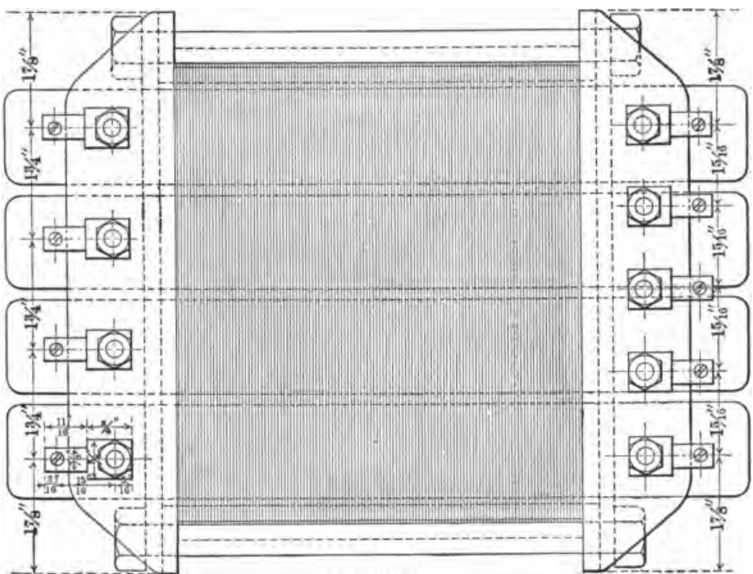
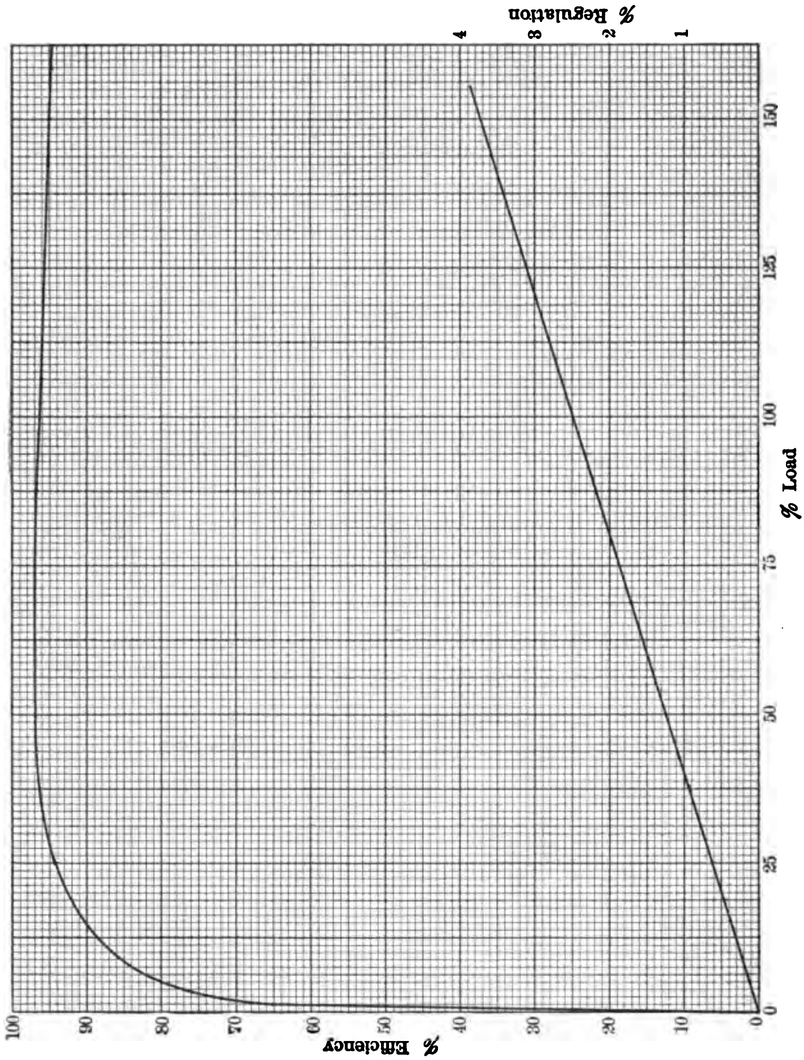


TOP VIEW

DESIGN No. 8—*Continued*



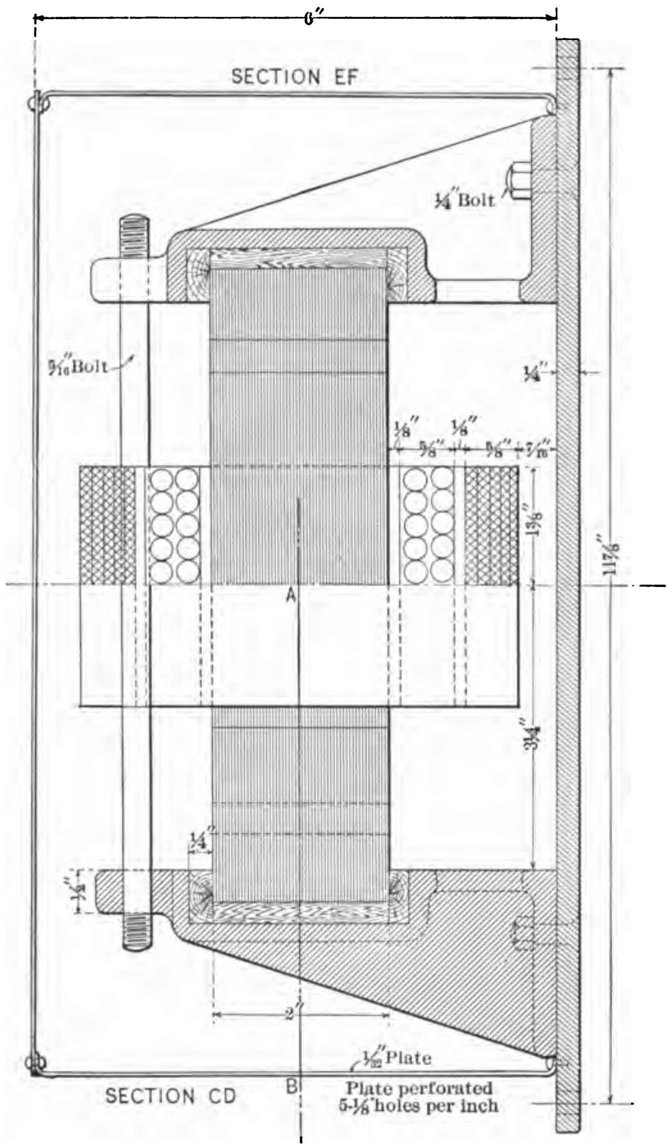
DESIGN No. 9

Transformer Suitable for Changing 110- to 120-Volt Alternating Current to 20-Volt Alternating Current for 20-Volt Tungsten or Mazda Lamps

Type	Distributed coil (core)
Capacity	1000 watts
Primary voltage	120
Secondary voltage	20
Frequency	60 cycles per second
Full load efficiency	93.5%
All day efficiency	84.8%
Copper loss	38.8 watts
Total core loss	29.5 watts

Windings.	Low Tension.	High Tension.
Number of coils	2	2
Turns per coil	20	120
Total turns	40	240
Size of wire	No. 2	No. 10
Resistance at 68° F	.0086	.219

DESIGN No. 9—*Continued*



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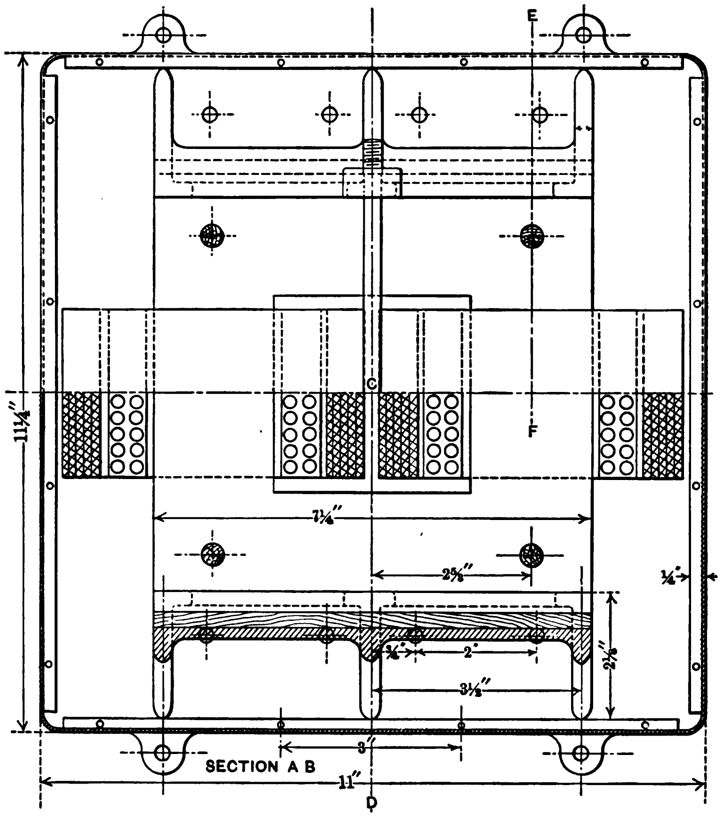
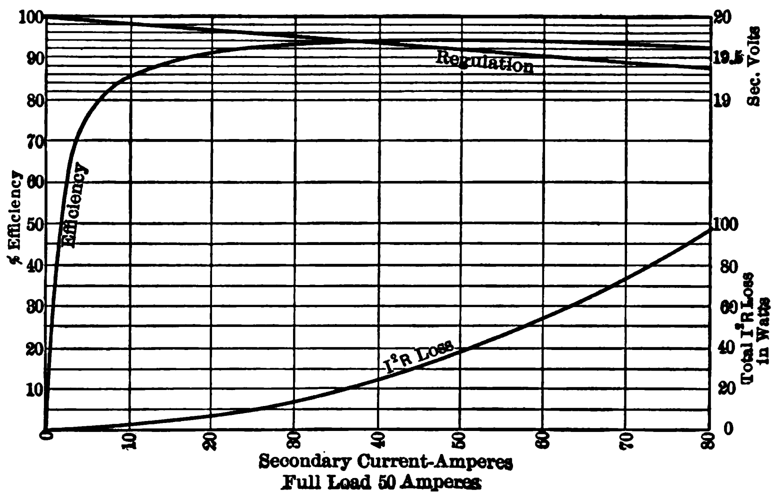


DESIGN No. 9—*Continued*

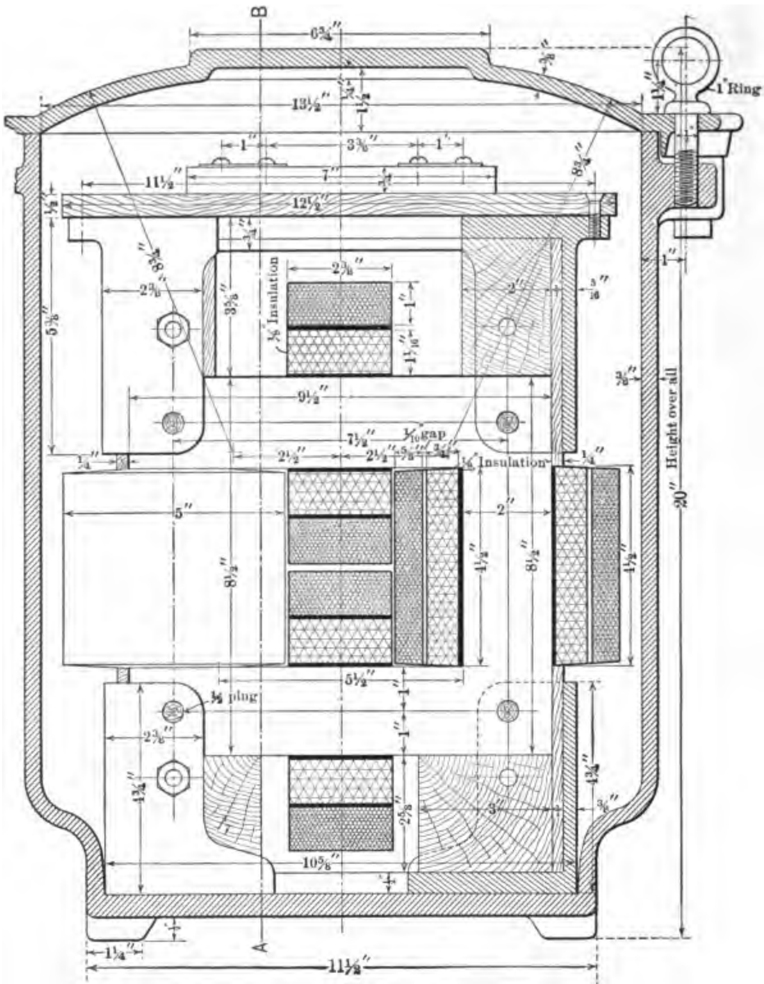


DESIGN No. 10

Type	Distributed coil
Capacity	5000 watts
Primary voltage	2200/1100
Secondary voltage	220/110
Frequency	60 cycles per second
Full load efficiency	96.7%
All day efficiency	90.7%
Copper loss	79.3 watts
Hysteresis loss	21.2 watts
Copper losses	79.3 watts
Total losses	165.1 watts

Windings.	Low Tension.	High Tension.
Number of coils	4	4
Turns per coil	56	560
Total number of turns	224	2240
Size of wire	No. 4	No. 14
Resistance at 80° C.	.554	10.0

DESIGN No. 10—*Continued*



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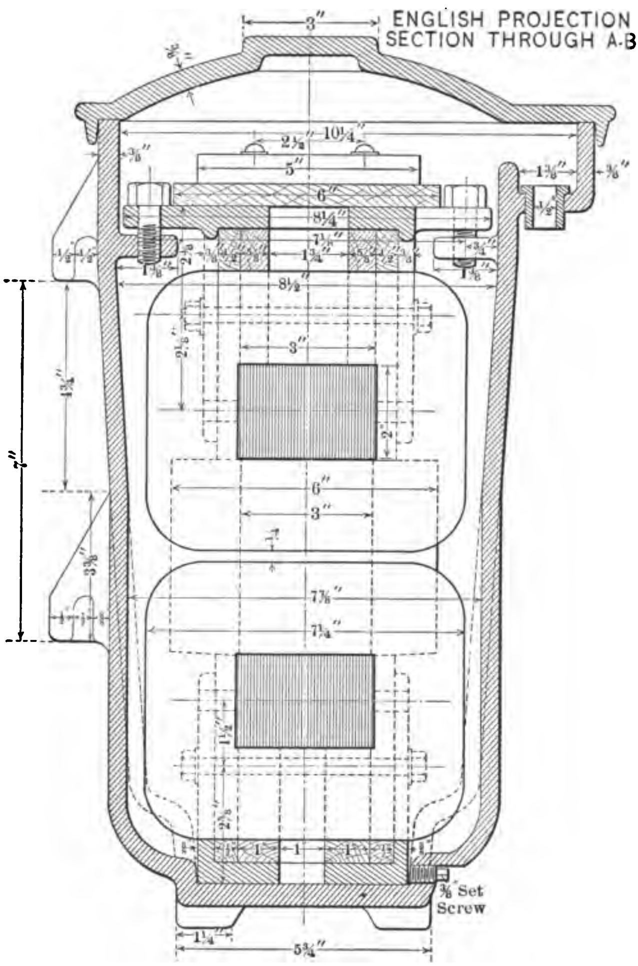

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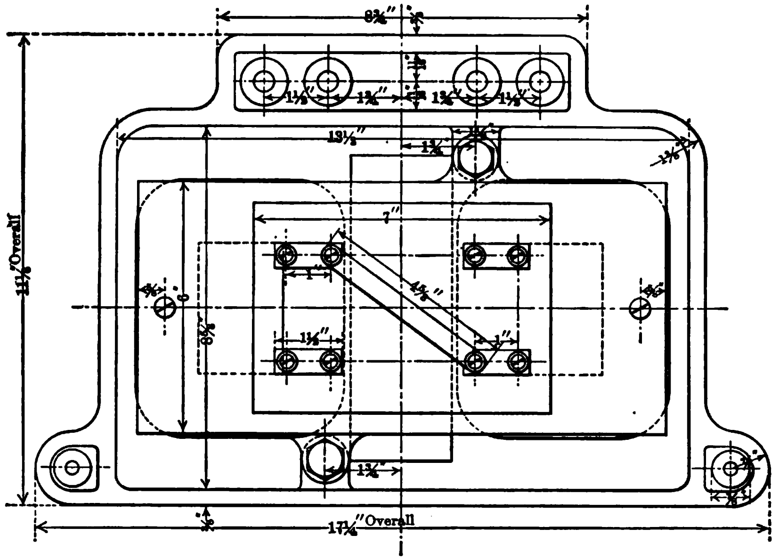
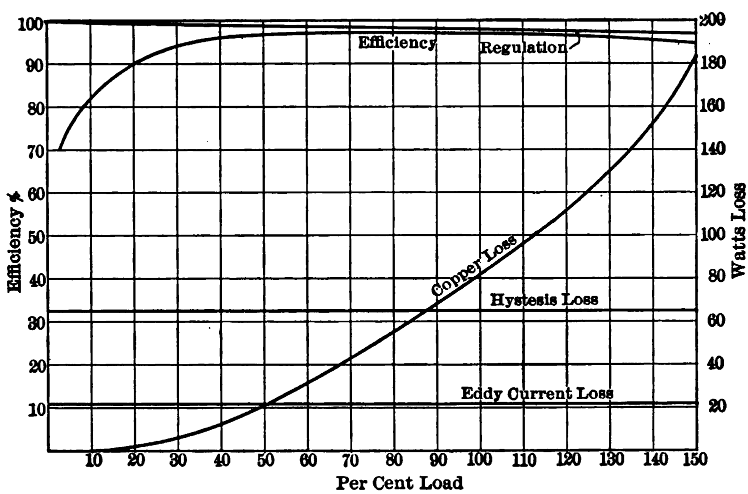




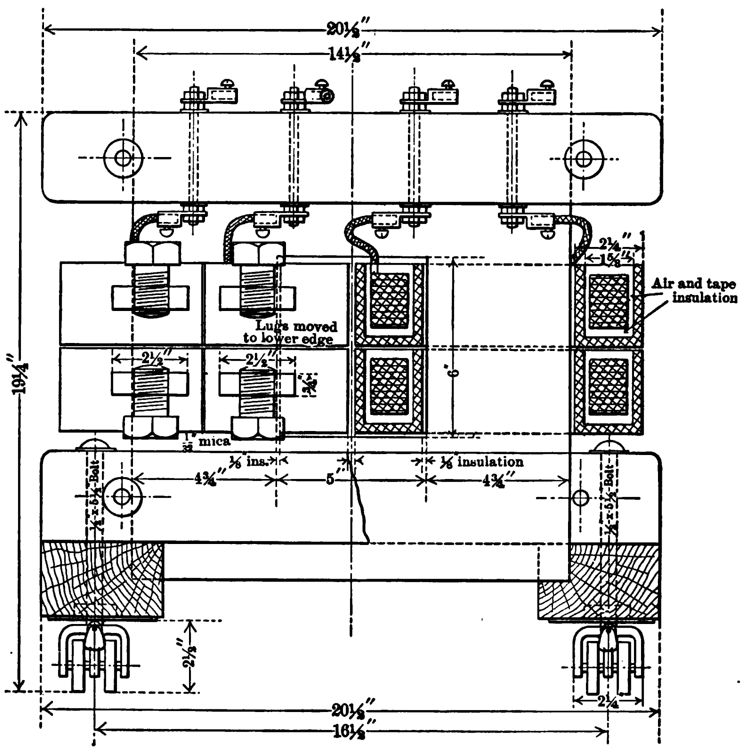
DESIGN No. 11

Welding Transformer, or Transformer for Large Currents at Low Electromotive Forces

Type	Distributed coils (core)
Capacity	7000 watts
Primary voltage	230/115
Secondary voltage	15/7.5
Frequency	60 cycles per second
Full load efficiency	96.1%
Hysteresis loss	115 watts
Eddy current	43 watts
Copper loss	138 watts

Windings.	Low Tension.	High Tension.
Number of coils	4	4
Turns per coil	1	30
Total number of turns	4	120
Size of wire	Castings	Ribbon

DESIGN No. 11—*Continued*



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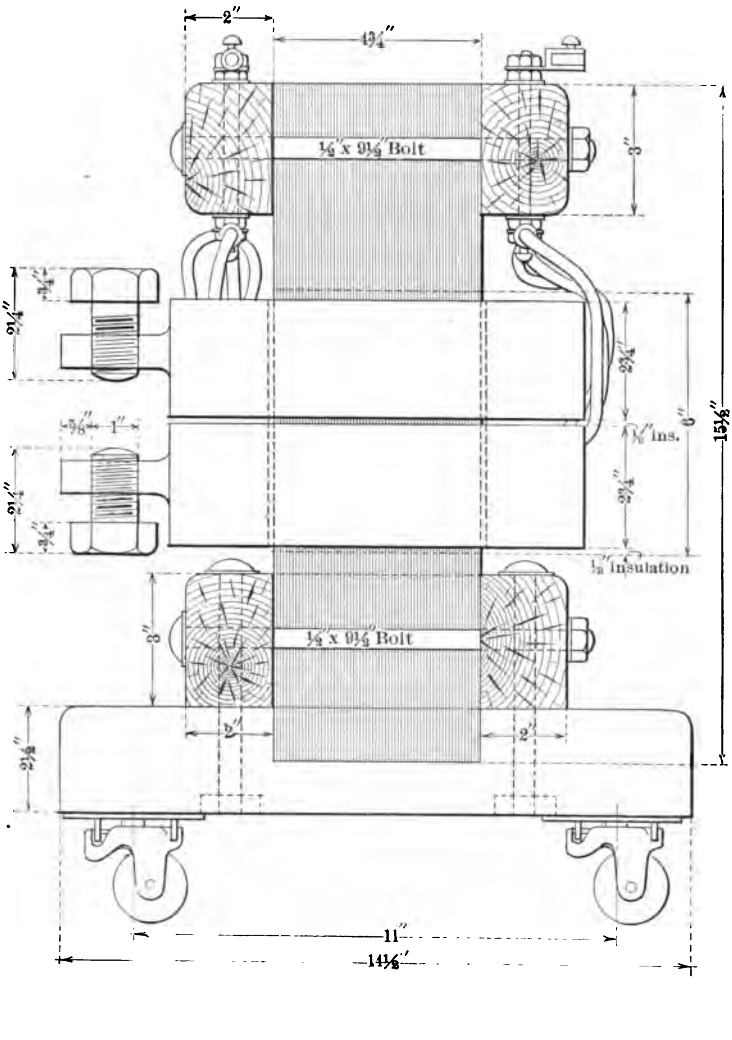

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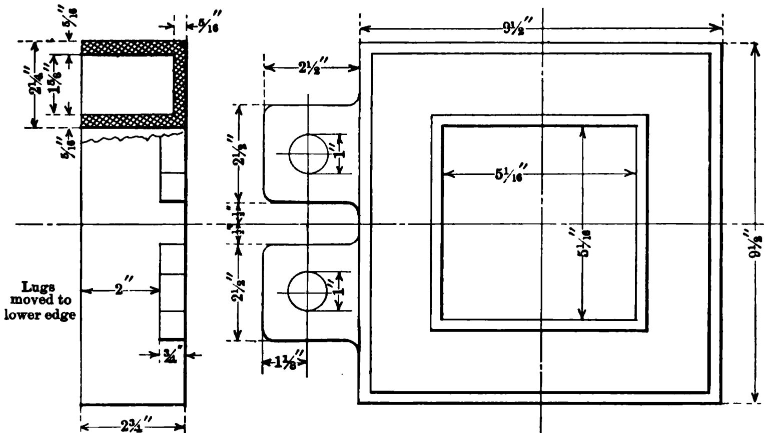
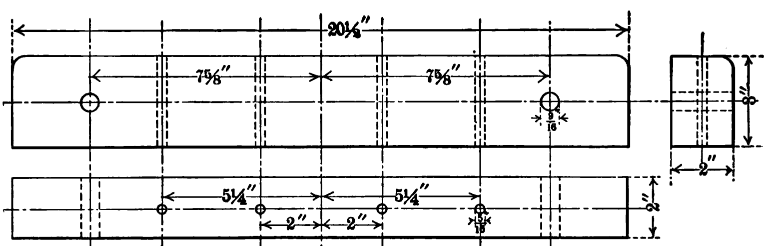
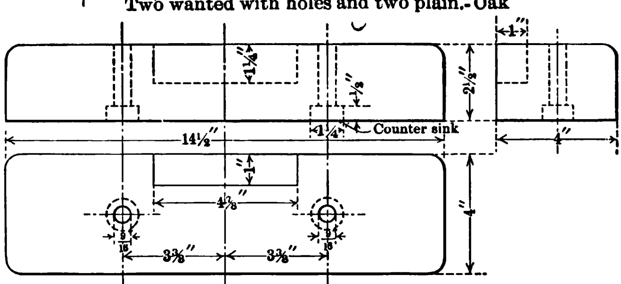


COPPER CASTINGS FOR SECONDARY

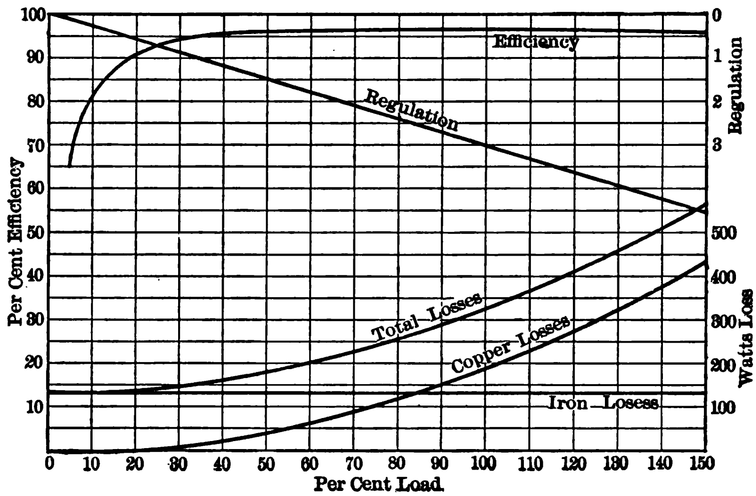


Two wanted with holes and two plain.- Oak



Two wanted-Oak

DESIGN No. 11—*Continued*



DESIGN No. 12

10-Kilowatt Auto-transformer, 230 Volts. 60 Cycles per Second

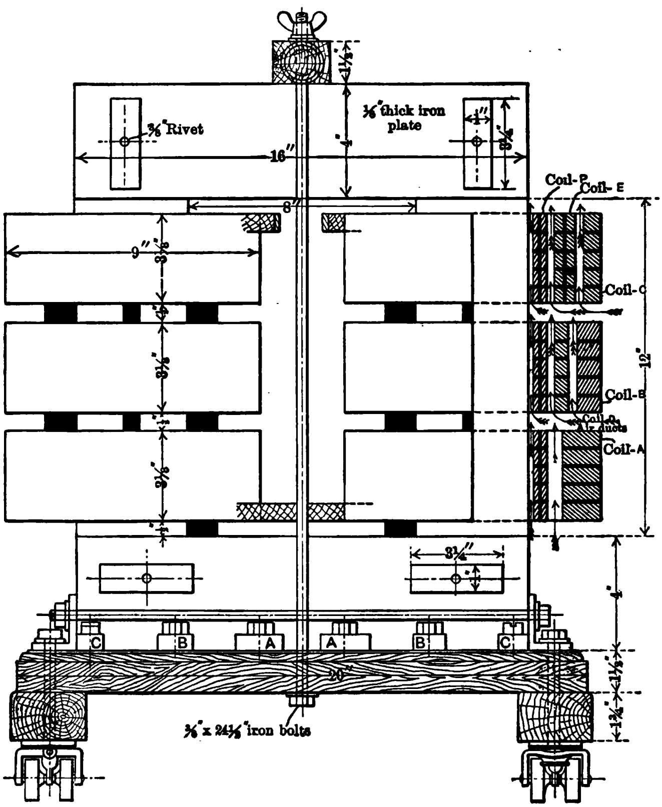
COILS.	STEPS.					
Coil A, 10 turns	10 layers	10 turns	230′ ½″×⅛″	copper strip .	Wt. =	55.2 lbs.
" B, 20 "	6 "	10 "	150′ ½″×⅛″	"	Wt. =	36.0 "
" C, 30 "	4 "	10 "	104′ ½″×⅛″	"	Wt. =	25.0 "
" D, 40 "	3 "	10 "	60′ ½″×⅛″	"	Wt. =	14.4 "
" E, 60 "	2 "	20 "	80′ ½″×⅛″	"	Wt. =	19.2 "
" P, 120 "	1 "	60 "	89′ ½″×⅛″	"	Wt. =	21.4 "
					Total Wt. =	171.2 lbs.

I^2R Losses at Various Per Cent Loads

Resistance	.10	25	50	75	100	125	150 %
Coil A, .000396	1.077	6.72	26.47	60.4	107.7	167.5	241.8 watts
η per cent.....	90.3	95.6	96.9	97.4	97.4	97.1	96.7 %
Coil B, .00172.	.785	4.97	19.88	44.8	78.5	120.8	179.0 watts
η per cent.....	90.3	95.6	97.2	97.6	97.5	97.4	97.0%
Coil C, .002522	.760	4.75	19.0	42.8	76.0	118.7	171.2 watts
η per cent.....	90.3	95.6	97.2	97.5	97.6	97.5	97.1 %
Coil D, .004072	.691	4.20	17.28	38.8	69.1	107.5	155.5 watts
η per cent.....	90.3	95.6	97.2	97.7	98.4	98.4	97%
Coil E, .0167..	.805	5.02	20.1	45.2	80.5	125.5	181.0 watts
η per cent.....	90.3	95.6	97.2	97.6	97.5	97.5	97.0%
Regulation %.	0	.113	.314	.517	.727	.93	1.13%
Coil P, .0297..	.586	3.65	21.5	32.9	58.6	91.4	151.0 watts

Hysteresis loss.. 44.564 watts
Eddy current loss....................................... 60.771 watts
Total core loss.. 105.335 watts
Volume iron in magnetic field............................ 78.4 cu.in.
Weight iron in magnetic field............................ 219.57 lbs.
Mean length of magnetic circuit..................... 56″ = 142.2 c.m.

DESIGN No. 12—*Continued*



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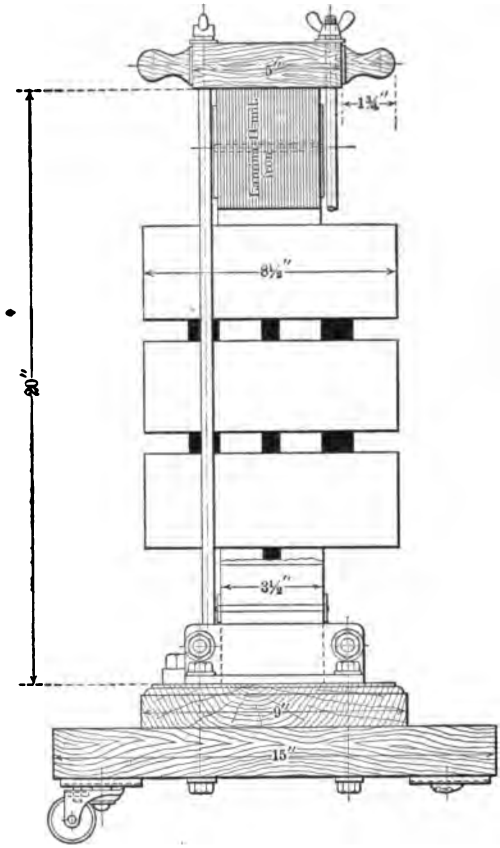

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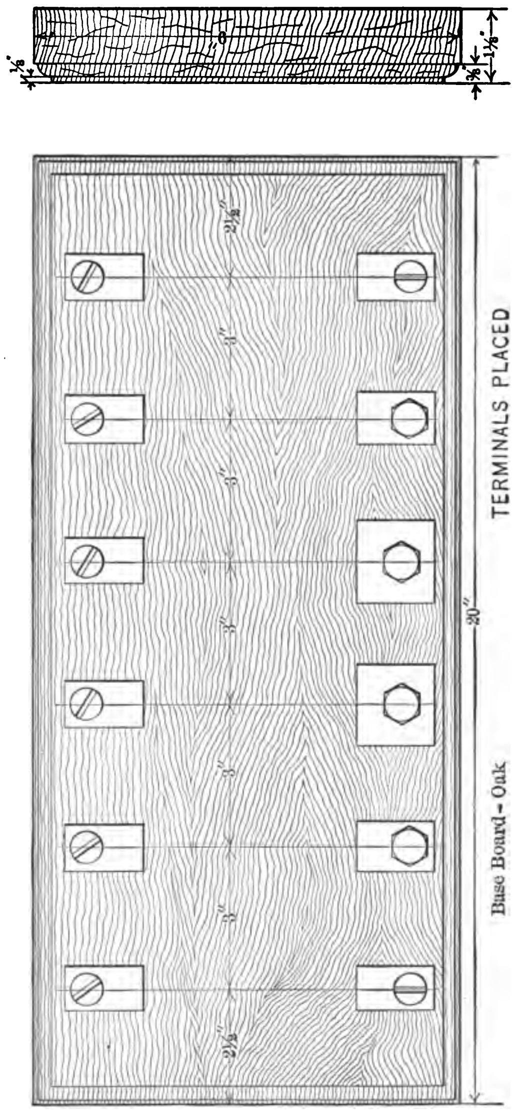

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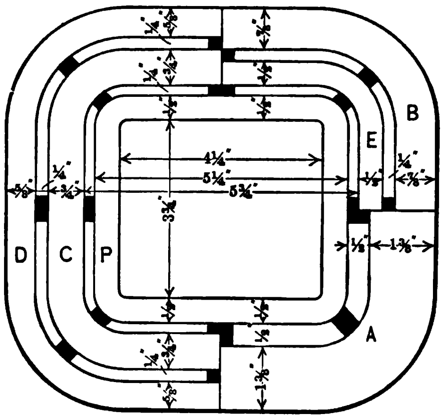
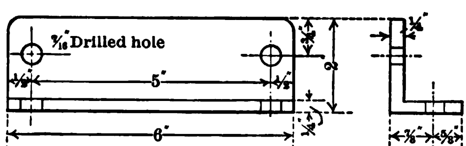
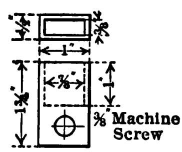


CROSS SECTION OF COIL



IRON CLAMP



BRASS TERMINALS

DESIGN No. 12—*Continued*

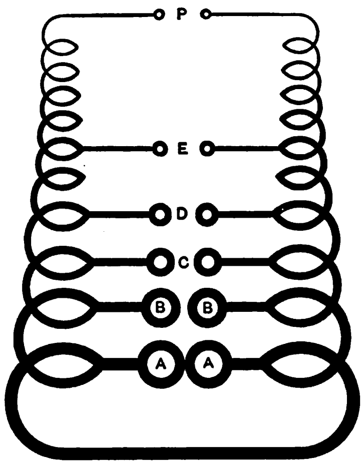
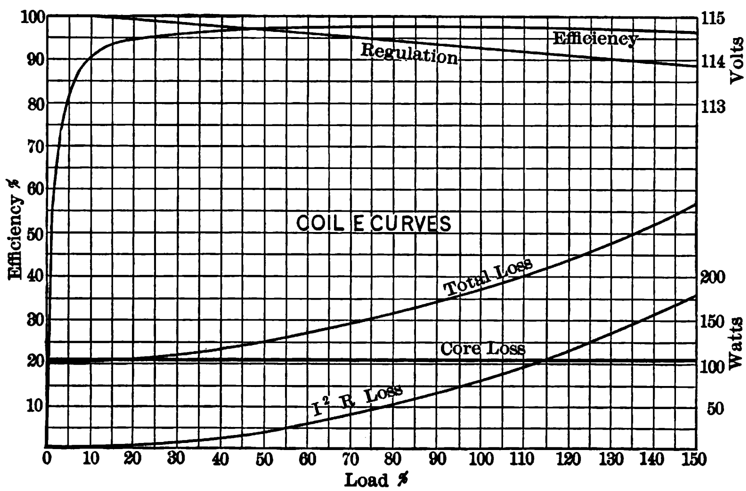


DIAGRAM OF WINDING



INDEX

A

PAGE
All-day efficiency 49
Angle of lag or lead 13, 47
Arc lighting transformer 21
Arc lamp regulator 22
Area of magnetic circuit 34
Area of conductors 39
Auto-transformer 24
" example of 108

B

Base board for laboratory transformer 111
Block terminal, example of 84
" " , connections 56
Brass terminals 112

C

Calculation, of efficiency 49
" , of magnetizing current 41
" , of no load current 41
" , of regulation 48
Case, design of 49
" , Western Electric 50, 51
" , Westinghouse 52
Coefficients of leakage 45
Coaxial coils on rectangular core 5
Copper castings for welding transformer 106
" losses 41
Constant current transformer 21
Core type transformer 5, 8, 82
Connections of transformer 56

PAGE

Cooling of transformer 49
Counter E.M.F. of self-induction 28
Cost of losses 17, 18
Current rushes at switching 28

D

Development of transformers 1
Design, method of 31
Designs, illustrative examples 57
Distributed coil types 8, 58, 81, 99
" iron types 9, 61, 67, 73

E

Eddy current loss 38
Efficiency, all-day 49
" , calculation of 49
" , conditions for high 17, 19
E.M.F., ratio of primary to secondary 31
Exciting current 26, 41
" " , magnetizing component 41
" " , energy component 41

F

Faraday's ring 2
Flux, tables of 33
" , linkage 32
Fixed charges 17

G

G. E. Co.'s type of magnetic circuits 9
Graphical diagram of pressure and current relations 13, 48

H

Heat losses 41
Hedgehog transformer 6
Hysteresis loss 38

I

Ideal transformer 47
Inductive load, regulation on 13, 15, 48

PAGE

Insulation.. 11
Iron losses.. 14, 38
Iron, volume of.. 38
" , permeability of.. 27

K

Kennedy's shuttle transformer.. 7

L

Lagging current effect on regulation.. 13, 15, 48
Leakage coefficients.. 45
" flux.. 43
Length of magnetic circuit.. 39
Losses.. 15, 41
Losses, how to divide.. 17

M

Magnetizing current.. 26, 41
Magnetic flux, tables of.. 17
" circuit, length of.. 39
" leakage.. 45

N

No load current, *see* Exciting current.
Non-inductive load, regulation on.. 13, 15, 48
Number of turns.. 32

O

Open circuit current, *see* Exciting current.
Oil-cooled transformer, radiating surface of case.. 49

P

Permeability, table of.. 27
Phase angles, effect of.. 13, 15, 48
Polyphase transformers.. 25
Power factor, effect on regulation.. 15, 48

PAGE

Pressure relations, graphical 13, 48
Primary current, for purpose of design 39
" " , for normal load 48
" " , on open circuits 26, 41

R

Radiating surface 49
Ratio of pressures 31
Reactance due to leakage 46
Regulation 48
Regulator, arc lamp 22
Resistance, primary coils 40
" , secondary coils 40
Rotary converter 12

S

Secondary E.M.F. 13, 31, 48
" , copper loss 41
" leads, method of connecting 56
Self-induction, due to leakage 46
Series transformer 23
Shuttle transformer 7
Spreading of coils to reduce leakage 4
Steinmetz, equation for hysteresis loss 38
" , " " eddy current loss 38
Subdivided coils on rectangular core 5
Subdivision of coils to reduce leakage 4

T

Table, of copper losses 14
" , of core losses 14
" , of efficiencies 14
" , leakage coefficients 45
" , permeabilities 27
" , total fluxes 17
Temperature rise 49
Three-phase transformers 26
Tests of transformers 19

PAGE

Transformer, illustrative designs.... 57
5 KW. Distributed coil.... 58
5 KW. Distributed iron.... 61
5 KW. Shell type.... 67
5 KW. Distributed iron.... 73
10 KW. Distributed iron.... 77
15 KW. Distributed coil.... 81
4 KW. Laboratory transformer.... 86
5 KW. Laboratory transformer.... 90
1 KW. 120 to 20 volt transformer.... 95
5 KW. Distributed coil.... 99
7 KW. Welding transformer.... 103
10 KW. Auto-transformer.... 108

V

Volume of iron.... 38

W

Wagner Co. illustrations.... 55, 56
Weight of copper.... 40
Western Electric Co. illustrations.... 36, 37, 50, 51, 53, 54
Westinghouse Co. illustrations.... 9, 10, 52, 54

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